March 3 1849

UNITED STATES
DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

EASTERN ENERGY AND LAND USE TEAM
BOX 705
Kearneysville, West Virginia 25430

Dear Colleague:

The Eastern Energy and Land Use Team (EELUT) is pleased to provide you this proceedings of the Acid Rain Symposium held at the 114th Annual Meeting of the American Fisheries Society at Cornell University on August 12-16, 1984. This publication is part of the series of technical reports on air pollution and acid rain developed at EELUT. Previous reports are listed on the inside front cover.

This AFS symposium posed the question, "Acid rain, is it a problem for fisheries?". Presentations by eight speakers, representing a diversity of backgrounds and viewpoints on the issue, provided a forum for discussion of the topic by the audience. Papers and abstracts from the presentations comprise this proceedings. They are printed as received from the authors and therefore reflect only their opinions and do not necessarily represent those of sponsoring agencies. We hope the papers will stimulate your thinking and research on the topic.

Please feel free to send your comments on this proceedings to EELUT.

Sincerely,

R. Kent Schreiber

R. Kent Schreiber
Acting Team Leader, EELUT

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Biological Report 80(40.21)
October 1985

Air Pollution and Acid Rain
Report No. 21

ACID RAIN AND FISHERIES: A DEBATE OF ISSUES

Symposium Proceedings
American Fisheries Society
114th Annual Meeting
August 12-16, 1984
Cornell University

Edited by

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Performed for:

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Division of Biological Services
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Fish and Wildlife Service

U.S. Department of the Interior

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DISCLAIMER

Although the research described in this report has been funded wholly or in part by the U.S. Environmental Protection Agency through Interagency Agreement No. EPA-82-D-X0581 to the U.S. Fish and Wildlife Service, it has not been subjected to the Agency's peer and policy review and therefore does not necessarily reflect the views of the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the Federal Government. This research has been funded as part of the National Acid Precipitation Assessment Program by the U.S. Fish and Wildlife Service.

This report should be cited as:

Rago, P.J. and R.K. Schreiber, eds. 1985. Acid rain and fisheries: a debate of issues. Symp. Proc., 114th Ann. Meet., Amer. Fish. Soc., August 12-16, 1984, Cornell Univ. U.S. Fish and Wildl. Serv. Biological Report 80(40.21). 106 pp.

PREFACE

The emergence of acid deposition as a national environmental concern in the late 1970's followed revelations of degradation of fish habitat in the Scandinavian countries. Several parallel examples have been found in North America, particularly in the Adirondack region of the United States and in western Ontario, Canada. Many differences have also been found. The complexity of the acid deposition problem, the difficulties in interpreting the evidence, and the potential economic consequences of regulatory action have all led to rather acrimonious debate within the United States and the international community. Numerous conferences have been held to present the latest scientific findings and their proceedings have been widely distributed. In 1984, another symposium on acid deposition was held at the 114th Annual Meeting of the American Fisheries Society with the purpose of focusing discussion on some of the more controversial aspects of acidic deposition and its effects on fish. To that end, scientists with disparate views on key issues were asked to present their case before the Society. This volume includes six of the papers presented at the symposium and two extended abstracts.

While it is widely agreed that reductions in pH have profound consequences for aquatic biota, the role of acid precipitation in increasing acidity has been disputed. The study of acidic deposition does not lend itself to simple experimentation on whole ecosystems or regions. Therefore most of the available evidence is derived from comparative surveys or, in some cases, comparisons of present conditions with historical field data. Most scientists have interpreted the available data as indicating a large number of water bodies are at risk but evidence of actual damage has been less strong.

The first paper, by Rosina Bierbaum, of the Office of Technology Assessment, provides an overview of the complexity of decision making at the National level and provides insight into the role of science in the legislative process. Two abstracts follow. In the first, A. Gordon Everett, a consulting geologist, suggests that natural processes and changes in land use practices must be considered as factors responsible for decreased pH in surface waters. In the second, George Hendry, along with Christopher Hoogendyk and Nicholas Gmur, accept the inadequacies of many existing data sets but suggest that the limitations can be circumvented by using a hierarchical approach. This technique explicitly recognizes the data constraints by using data to address questions at successively higher levels of resolution.

Absence of fish species from lakes has been one of the primary pieces of evidence to argue the case of adverse acid deposition effects. Yet it is well known that many other factors influence fish species richness. Frank Rahel , using data on Wisconsin lakes, demonstrates that the estimate of fish species loss cannot be based on pH alone. Lakes with naturally low alkalinity have fewer species than comparably sized lakes with high alkalinity. Another potentially confounding factor in the interpretation of existing data is the role of aqueous calcium and aluminum. Chris Ingersoll, T.W. La Point, J. Breck and H.L. Bergman present recent experimental evidence which demonstrates that low pH and aluminum act to decrease hatching in brook trout. Calcium, usually considered to mitigate the effects of low pH and aluminum, did not exert any protective effect until after hatching.

Some of the best documented cases for the adverse effects of low pH come from Ontario lakes. Gail Beggs and J.A. MacLean, along with J.G. Gunn, M.L. Jones and K. Minns, summarize field and laboratory evidence for Ontario and describe ongoing research programs. Particularly noteworthy are their attempts to verify predictive models with both survey data and long term studies.

Gwyneth Howells, director of biological research for the Central Electricity Board of the United Kingdom, reviews existing European data. She concludes that the uncertainties in the relationships among acidic deposition and lake chemistry and species presence militate against imposition of regulations at this time. Even if reductions can be made, the likely benefits will not be realized for decades to come.

Terry Haines, C.H. Jagoe, and S.J. Pauwels present new data on fish surveys in Maine and Vermont. Lakes above pH 6.0 show no relation between pH and the number of fish species present or catch per unit effort. In lakes below pH 6.0 however, pH was negatively correlated with both species richness and relative abundance. Nearly identical patterns were found in Maine and Vermont, suggesting that their results may hold for much of northern New England.

The papers herein often present conflicting viewpoints. We have not attempted to reconcile these contradictions in an attempt to highlight the major points of controversy. The views presented do not necessarily represent those of the sponsoring agencies, Fish and Wildlife Service or the Environmental Protection Agency. We hope that these papers will contribute to the timely debates of acid deposition effects and emphasize some of the more important scientific questions awaiting resolution.

Paul J. Rago
Symposium Chairman

R. Kent Schreiber
Co-Chairman

TABLE OF CONTENTS

Page

PREFACE iii
TABLES vii
FIGURES viii
ABSTRACTS 1
  The Congressional Dilemma - Decision Making in the Face of Uncertainty 2
  Fish Community Interactions, Biogeographic Factors and Lake Acidity 3
  Early Life Stage Brook Trout Experiment to Determine the Effects of pH, Calcium and Aluminum in Low Conductivity Water 4
  The Case for Effects of Acidic Deposition on Ontario's Fisheries 5
  Causes and Mechanisms of Fishery Decline 6
  Fish Species Distribution as a Function of Lake Acidity in Northeastern United States 7
The Congressional Dilemma: Decision-Making in the Face of Uncertainty by Rosina M. Bierbaum 8
  Introduction 9
  Risks to Aquatic Resources 13
  Choices Facing the Congress 15
  Designing a Control Proposal 16
  Recent Legislative Proposals 21
  References 25
Factors Contributing to the Complexity of the Acid Deposition Surface Water Acidification Problem by A.G. Everett 26
Detecting Region-wide Trends in Surface Water Quality by George R. Hendry 28
Biogeographic Influences, Species Interactions and Lake Acidification by Frank J. Rahel 30
  Introduction 31
  Methods 31
  Results and Discussion 32
  References 40

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Page

An Early Life Stage Brook Trout Experiment to Determine the Effects of pH, Calcium, and Aluminum in Low Conductivity Water by C.G. Ingersoll, T.W. La Point, H.L. Bergman, and J. Breck 42

Introduction 43

Methods 43

Results and Discussion 44

References 48

The Case for Effects of Acid Deposition on Ontario Fisheries by G.L. Beggs, J.A. MacLean, J.G. Gunn, M.L. Jones, and K. Minns 49

Introduction 51

The Current Evidence for Impact in Ontario 51

Research Programs in Ontario 54

Conclusions 59

References 60

Mechanisms and Causes of Fishery Decline by G.D. Howells 62

Introduction 63

Evidence for Changed Fishery Status and Water Quality 63

Experimental Studies 72

Restoring Fisheries 74

References 78

Fish Species Distribution as a Function of Lake Acidity in the Northeastern United States by Terry A. Haines, Charles A. Jagoe and Stanislas J. Pauwels 82

Introduction 84

Vermont 85

Maine 89

Discussion 94

References 95

BEST COPY AVAILABLE

TABLES

Table Page

1 Acid deposition related bills of the 98th Congress 23

2 Use of species-area regressions to predict fish species richness for 33 low-alkalinity, northern Wisconsin lakes 34

3 Comparison of fish species composition among Wisconsin lakes differing in surface area, alkalinity and isolation 37

4 Exposure matrix for aluminum, pH and calcium 43

5 Improvements in Joe Lake water chemistry 52

6 Water chemistry on lake trout spawning shoals 53

7 Comparison of water quality with observed fishery status 64

8 Chemistry of fishless streams in the UK 72

9 Summary of fish distribution by pH class for 289 waters with concurrent fish surveys and water chemistry (1975-1982) 84

10 Physical and chemical data for 22 lakes surveyed in Maine 89

11 List of fish species found in the 22 lakes surveyed in Maine 90

BEST COPY AVAILABLE

FIGURES

Figure Page

1 Transported air pollutants: emissions to effects 10

2 Sulfur dioxide and nitrogen oxides emissions - state totals for 1980 10

3 Sulfur dioxide and nitrogen oxides emissions trends - national totals, 1900 - 2030 11

4 Average sulfur transport distances across eastern North America 12

5 Regions of the eastern United States with surface waters sensitive to acid deposition 14

6 Precipitation acidity - annual average pH for 1980, weighted by precipitation amount 17

7 Target value: average precipitation pH of 4.6 18

8 Cost of reducing sulfur dioxide emissions by 10 million tons per year, nationwide increases in annual-average electricity bills for a typical residential consumer 20

9 Relationship between the number of fish species and $\log_{10}$ for high-alkalinity and low-alkalinity lakes in northern Wisconsin 33

10 The effect of pH, aluminum and calcium on brook trout survival through day 40 45

11 Partial correlation coefficients of the response of brook trout to calcium, aluminum or log H^+ 46

12 Stepwise linear regression of the effect of aluminum and calcium on brook trout survival through day 40 at pH 4.4 47

13 Frequency distribution of fork lengths of native brook trout caught in Whitepine Lake in 1982 and 1983 52

14 Inflection point alkalinity and pH of 605 Ontario brook trout lakes 55

15 The relationship between catch-per-unit-effort of native lake trout and mid-lake, summer epilimnetic pH in 24 Ontario lake trout lakes . 56

16 Age composition of white suckers captured in Westward Lake in 1969-70 and 1982 57

17 Chemical balance in fishless lakes (.) and in good or overpopulated lakes (x) in Sorlandet 65

BEST COPY AVAILABLE

Figure Page

18 Fishery status of South Norway lakes of pH 5.2 - 5.4 66

19 Changes in 55 Swedish lakes 1971-76 67

20 Species diversity in Swedish char lakes 68

21 Fish stocked and fishing pressure in Adirondacks, 1940 to 1980 69

22 The status of brook trout populations (Welsh and Pennine streams) .. 71

23 Percentage survival of brown trout eggs at pH 4.5 72

24 Predicted and observed fishless lakes, S. Norway 73

25 Relationship between the percentage of lakes with lost trout population and pH for lakes in four counties in southernmost Norway 75

26 Fishery status of lakes in southern Norway predicted for changes in non-marine sulfate concentration 76

27 Distribution of lake pH for 1,047 Adirondack Mountain region lakes located at elevation below and above 2,000 ft 85

28 Regression of log (number of fish species + 1) on pH for 29 Vermont lakes 86

29 Regression of log (catch per unit effort + 1) on pH for 29 Vermont lakes 87

30 Geographical distribution and pH category for 23 lakes surveyed in Maine 88

31 Distribution of fish species by lake pH 91

32 Regression of log (number of fish species + 1) on pH for 22 Maine lakes 92

33 Regression of log (catch per unit effort + 1) on pH for 22 Maine lakes 93

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ABSTRACTS

THE CONGRESSIONAL DILEMMA - DECISION MAKING IN THE FACE OF UNCERTAINTY

Rosina M. Bierbaum, Office of Technology Assessment, Washington, D.C.

Reports of natural resource damage in this country and Canada, Scandinavia, and West Germany have made transported air pollutants, particularly acid rain, a focus of scientific and political controversy. The Clean Air Act, the major piece of federal legislation governing air quality in the United States, addresses local air pollution problems but does not directly apply to pollutants that travel many miles from their sources. Many individuals and groups, pointing to the risks of environmental degradation, are calling for more stringent Federal pollution controls. Others contend that the risks of economic dislocations resulting from a control program will not be justified and that any control strategy designed with current scientific knowledge may be inefficient.

Five key uncertainties are especially relevant to Congressional decisions about transported air pollutants. These include controversies about 1) the extent and location of current damages, 2) future damages (whether they are cumulative and/or irreversible), 3) geographic origins of observed levels of pollution, 4) the effectiveness of emissions reductions for decreasing observed levels of transported pollutants, and 5) whether the ongoing research program will provide significant new results.

There are four major approaches currently available for Congressional action on transported air pollutants:

- mandating emissions reductions to further control the sources of transported pollutants;
- liming lakes and streams to mitigate some of the effects of acid deposition;
- modifying the Federal acid deposition research program to provide more timely guidance for Congressional decisions; and
- modifying existing sections of the Clean Air Act to enable EPA, states to more effectively address some aspects of transported air pollutants

Most legislative proposals in the 98th Congress (12 out of 19) have concentrated on Option 1. Mandating further emissions reductions would require the Congress to make a number of interrelated choices. These include decisions about which pollutant emissions to reduce, from what source regions, by how much, and over what time period. Congress would also need to choose specific policy mechanisms to implement the reductions, allocate their costs, and address undesired secondary consequences of emissions reductions. Several of these bills will be examined to show how different answers to these questions can produce significantly different control programs.

FISH COMMUNITY INTERACTIONS, BIOGEOGRAPHIC FACTORS AND LAKE ACIDIFICATION

Frank J. Rahel, The Ohio State University, Columbus, Ohio

Relating changes in fish communities to acidification requires a knowledge of community composition prior to acid inputs. In the absence of reliable historical data, comparative biogeographic studies can be used to predict fish community structure from readily available limnological and morphometric data. A comparison of two groups of Wisconsin lakes that differ in their sensitivity to acidification revealed significant differences in fish community composition. Small, low-alkalinity lakes that are highly vulnerable to acid inputs lack many fish (including darters, walleye, sculpin and most cyprinids) that are common in nearby lakes which are less vulnerable to acidification because of higher alkalinity. None of these lakes had been culturally acidified and thus, these patterns reflect the influence of biogeographic factors (small size, low productivity, lack of inlet/outlet streams) and biotic interactions in structuring lake fish communities. In another example, small seepage lakes forming a lake successional gradient contained one of three distinct fish assemblages depending upon lake size, habitat heterogeneity, pH and winter oxygen concentrations. These environmental factors were good indicators of the type of fish community likely to be present. Studies such as these can be used to predict fish community composition in unsampled lakes or for earlier time periods (e.g., prior to acidification). Problems of resolution (e.g., predicting species richness vs. assemblage type vs. occurrence of particular species) will be discussed.

Species-area relationships, used to estimate how many fish populations have gone extinct in acidified lakes, may overestimate the number of extinctions if regression equations developed from unacidified lakes (which have high alkalinity) are used to predict the number of fish species which should be present in acidified lakes (which had low alkalinity). In a group of Wisconsin lakes, the species-area regression for alkaline lakes had a higher intercept and greater slope than the regression for low-alkalinity, but unacidified lakes. Thus, small, low-alkalinity lakes have fewer fish species than small, alkaline lakes and add species at a slower rate as lake size increases.

AN EARLY LIFE STAGE BROOK TROUT (*Salvelinus fontinalis*) EXPERIMENT TO DETERMINE THE EFFECTS OF pH, CALCIUM, AND ALUMINUM IN LOW CONDUCTIVITY WATER

C.G. Ingersoll, T.W. La Point, H.L. Bergman, University of Wyoming, Laramie, WY; and J. Breck, Oak Ridge National Laboratory, Oak Ridge, TN

Brook trout eggs were exposed to varying levels of pH, calcium, and aluminum totaling 64 different combinations. The levels of pH, aluminum, and calcium were chosen to represent the chemistry of sensitive lakes and streams in eastern Canada, the northeastern United States, and Scandinavia. As aluminum and acidity increased, the frequency at which embryos failed to escape from the chorion during hatching also increased, usually resulting in the death of the embryo. The effects of aluminum and low pH become evident during the hatching process and continue through yolk absorption, while the protective effects of calcium are not noted until after hatching.

AN EXAMINATION OF THE CASE FOR EFFECTS OF ACIDIC DEPOSITION ON ONTARIO'S FISHERIES

Gail Beggs, J. MacLean, Ministry of Natural Resources, Fisheries Branch, Toronto, Ontario; John Gunn, Ministry of Natural Resources, Sudbury, Ontario; Michael Jones, Environmental and Social Systems Analysts, Ltd., Toronto, Ontario; K. Minns, Department of Fisheries and Oceans, Burlington, Ontario

A coordinated program of studies is being conducted to examine the impacts of acidic precipitation on fisheries resources in Ontario. The focus for these studies has been the development of models that predict both the extent and rate of impacts and the uncertainties inherent in these predictions. Data on water chemistry and fish communities in lakes across the province are being collected and compiled. Field and laboratory studies are being conducted to determine the levels of pH and aluminum that early life history stages of fish are being exposed to and the effects of this exposure on their survival. Experiments are also being used to determine the cause of observed failures in recruitment of fish in sensitive lakes. With these studies as a background, the case for the effects of acidic deposition on fisheries resources in Ontario will be critically examined.

CAUSES AND MECHANISMS OF FISHERY DECLINE

Gwyneth Howells, Central Electricity Generating Board, Surrey, UK

The evidence of changing fishery status in acid waters (especially European waters) will be reviewed. Waters of approximately pH 5 or below may be acutely toxic to young fish if calcium is below a threshold concentration of 1 ppm. Aluminum is also toxic at low concentration when pH is around 5 to 5.5. Over the longer term, however, older fish can tolerate and continue to grow in acid waters of pH 5 but there are reports that reproduction is impaired in scarcely acid waters of approximately pH 6. Modelling population status on the basis of field data and laboratory bioassay, however, does not give a good correspondence between observed and predicted status, suggesting that other factors than water quality may be operating. These might include general environmental conditions such as temperature, latitude, lake size and complexity which are known to influence the variety of species in mixed communities. Another factor, not yet known in sufficient detail, could be the effect of transient changes in water quality associated with episodic events.

On present evidence, the benefits of S emission control in bringing surface water quality within the range of acidity, calcium and aluminum concentrations suitable for fish seems quite uncertain. It is, however, demonstrably feasible and economic to improve conditions in acid susceptible areas by lime application, hydrological control, or vegetation management. These treatments can improve acid, specifically in affected areas, waters within shorter time scales than could be achieved by the widespread implementation of S control.

FISH SPECIES DISTRIBUTION AS A FUNCTION OF LAKE ACIDITY IN THE NORTHEASTERN UNITED STATES

Terry A. Haines, U.S. Fish and Wildlife Service, Field Research Station, University of Maine, Orono, ME; C.H. Jagoe and S.J. Pauwels, University of Maine, Orono, ME

The Northeastern United States now receives precipitation of annual weighted mean pH of 4.3 - 4.4. A substantial portion of the surface waters in this region are low in alkalinity and are believed to be vulnerable to acidification. In order to test the hypothesis that acidic precipitation has reduced the pH of sensitive surface waters and resulted in the elimination of sensitive fish species, a survey was made of the water chemistry and fish populations of 20 lakes in Maine. The lakes were located in areas where surface water alkalinity was low, had not been reclaimed or stocked, and were similar in physical characteristics. Five of the lakes had been previously surveyed by state agencies. The lakes had mean pH values of 4.7 to 7.0.

There were no fish present in two lakes with pH 4.7 - 4.9. All other lakes with pH > 5.0 contained fish. There was no relationship between the number of species or catch per unit effort and lake acidity for lakes that contained fish. Comparison of recent and historical water chemistry and fish species data for lakes that had previously been surveyed indicated that the lakes were slightly lower in pH and alkalinity, but the number and type of fish species present had not changed.

THE CONGRESSIONAL DILEMMA

Decision-Making in the Face of Uncertainty

by

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Washington, D.C. 20510

The views expressed in this paper are entirely those of the author and not necessarily those of OTA.

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INTRODUCTION

My role here today is to tell you about recent Congressional "activity" -- I won't say "action" -- on the issue of acid deposition. I work for the Congressional Office of Technology Assessment (OTA), perhaps the closest thing that Congress has to an academic institution. We conduct 6 month to 4 year-long studies on topics timely to the legislative agenda. Since the Clean Air Act is up for reauthorization, the Senate Committee on Environment and Public Works and the House Committee on Energy and Commerce asked OTA to summarize the risks of acting to control transported air pollutants now versus the risks of waiting. On the one side are risks of unnecessary or inefficient control costs. On the other, are possible ecological damages while waiting for more detailed research results. Both kinds of risks have distributional consequences.

OTA does not make recommendations -- in fact, it is forbidden to by law. We present an array of feasible options; the idea is to elevate the subsequent Congressional discussion to a more informed level so both sides of an issue can argue with the best available information.

For the past four years, I've been working with the Committees active in proposing acid rain legislation. Today, I hope to give you some idea of how the current bills evolved, the considerations they incorporate, and how they deal with the many scientific uncertainties that still exist.

First, I've been asked to spend a few minutes reviewing the problem. Transported air pollutants result from the emission of three primary pollutants: sulfur dioxide, nitrogen oxides, and hydrocarbons. As these pollutants are carried away from their sources, they can be transformed through complex chemical processes into secondary pollutants. Acid deposition results when sulfur and nitrogen oxides and their transformation products return from the atmosphere to the Earth's surface in either wet form as rain, snow, fog or dew (called acid precipitation) or dry as gases or particles (see figure 1).

During 1980, some 27 million tons of sulfur dioxide and 21 million tons of nitrogen oxides were emitted in the United States. Figure 2 displays the regional pattern of emissions. About 80 percent of the sulfur dioxide and 65 percent of the nitrogen oxides came from within the 31 states bordering or east of the Mississippi River. Figure 3 shows how these emissions have varied since 1900. Since 1940, sulfur dioxide emissions increased by about 50 percent and nitrogen oxides emissions about tripled. Throughout the same period, taller emission stacks became common, allowing pollutants to travel farther.

Figure 3 also shows a range of projected future emissions of these pollutants, assuming that current air pollution laws and regulations remain unchanged. By 2030 -- the end of the projection period -- most existing facilities will have been retired. Despite relatively strict pollution controls mandated for new sources by the Clean Air Act, emissions of both sulfur and nitrogen oxides are likely to remain high for at least the next half century -- a time period many ecologists feel is long enough to be significant to natural ecosystems.

The transported air pollutants considered in this study result from emissions of three pollutants: sulfur dioxide, nitrogen oxides, and hydrocarbons. As these pollutants are carried away from their sources, they form a complex "pollutant mix" leading to acid deposition, ozone, and airborne fine particles. These transported air pollutants pose risks to surface waters, forests, crops, materials, visibility, and human health.

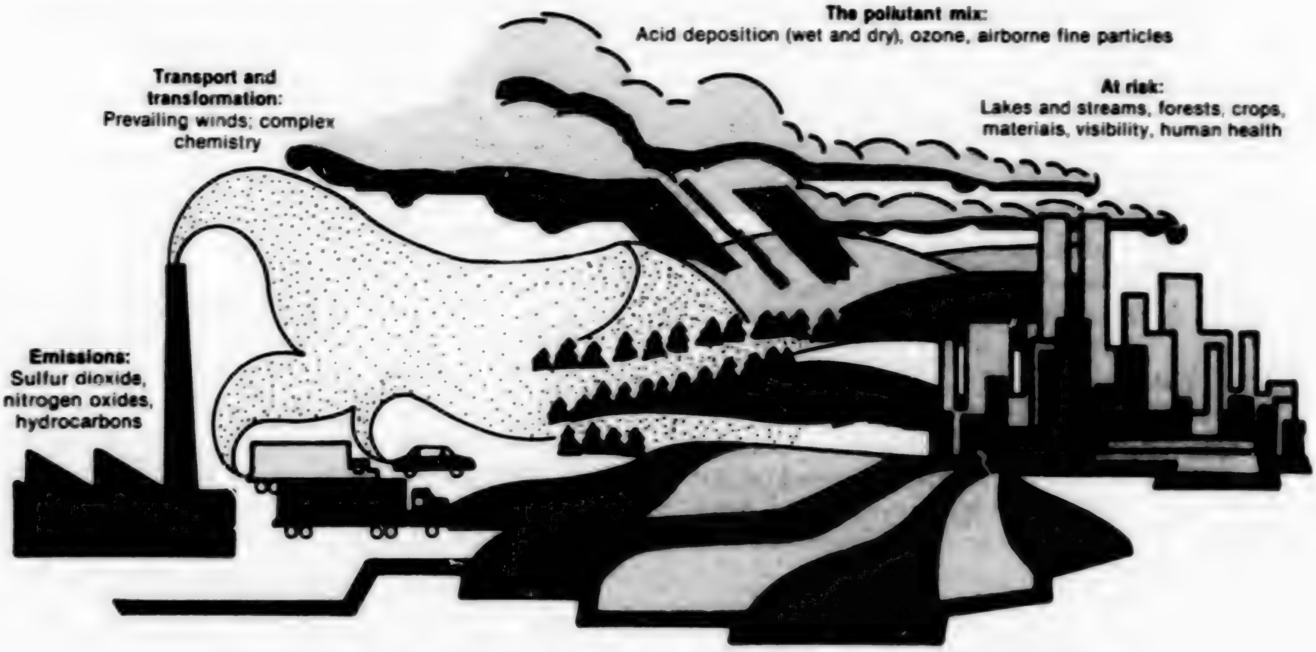
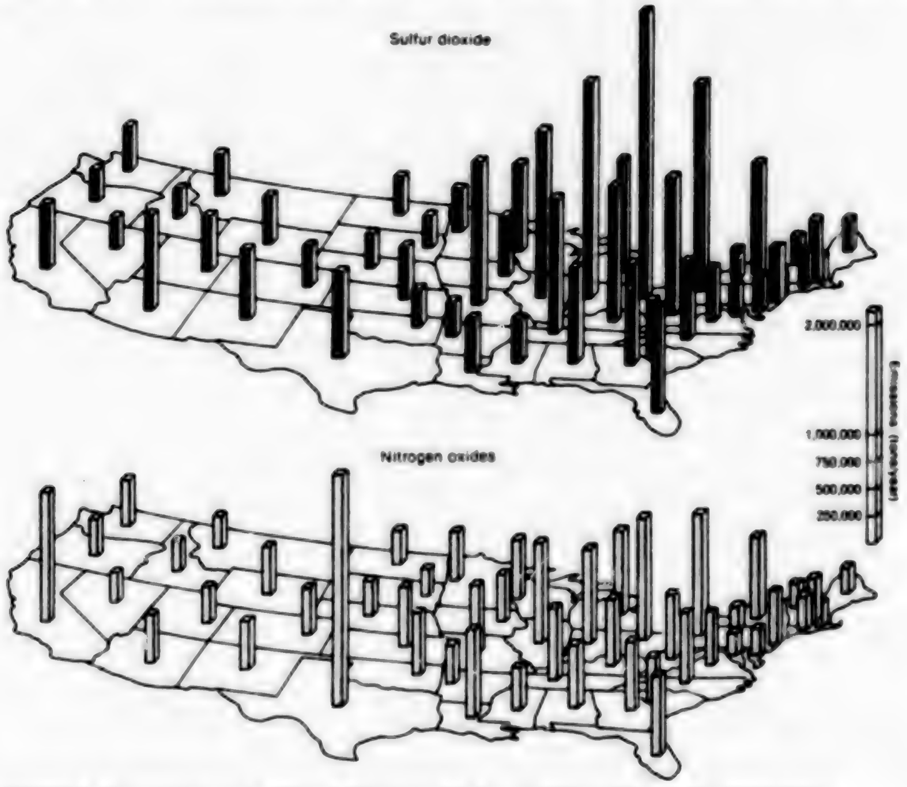
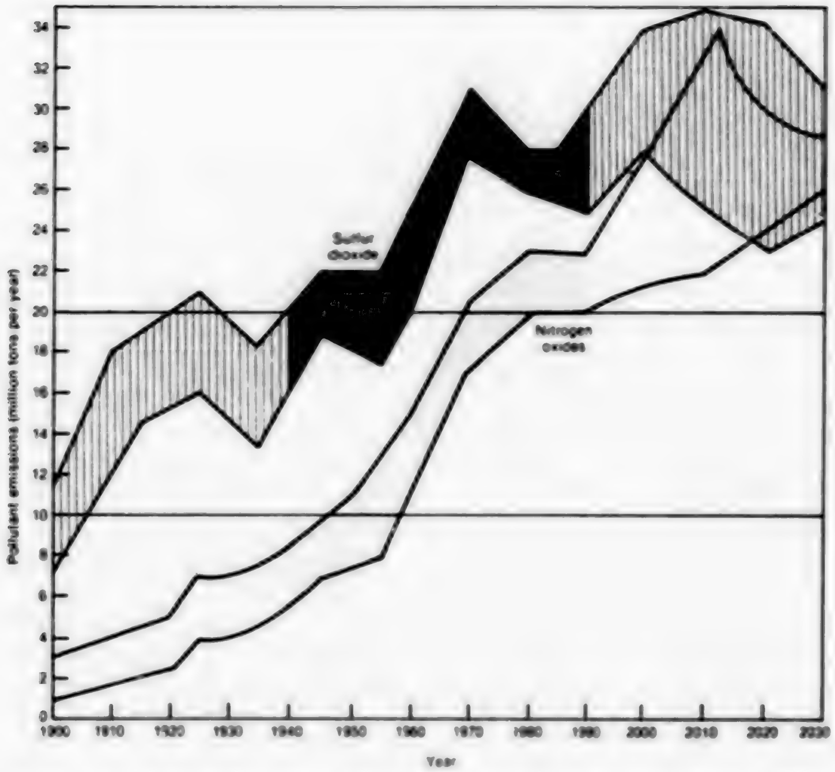

The pollutant mix:
Acid deposition (wet and dry), ozone, airborne fine particles
Transport and transformation:
Prevailing winds; complex chemistry
At risk:
Lakes and streams, forests, crops, materials, visibility, human health
Emissions:
Sulfur dioxide, nitrogen oxides, hydrocarbons

Figure 1. Transported Air Pollutants: Emissions to Effects



SOURCE: G. Gschwandtner, et al., "Historic Emissions of Sulfur and Nitrogen Oxides in the United States From 1900 to 1980," draft report to EPA, 1983.

Figure 2. Sulfur Dioxide and Nitrogen Oxides Emissions - State Totals for 1980



The graph above displays estimates of historical emissions, and projections of future emissions of sulfur dioxide and nitrogen oxides. Pre-1940 estimates and post-1990 projections are subject to considerable uncertainty. Projections of future emissions incorporate a wide range of assumptions about future economic growth, energy mix, and retirement of existing facilities; they assume no change in current air pollution laws and regulations.

SOURCES: Office of Technology Assessment. Composite from: U.S. Environmental Protection Agency, "National Air Pollution Emission Estimates, 1940-1980," 1982; G. Gschwandtner, et al., "Historic Emissions of Sulfur and Nitrogen Oxides in the United States From 1900 to 1980," draft report to the U.S. Environmental Protection Agency, 1983; *Emissions, Costs and Engineering Assessment*, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, 1982; and "Summary of Forecasted Emissions of Sulfur Dioxide and Nitrogen Oxides in the United States Over the 1980 to 2010 Period," ICF Inc. and NERA for the Edison Electric Institute, 1982; forecasts 1980 to 2030 by E. H. Pechan & Associates, Inc., for the Office of Technology Assessment, 1984.

Figure 3. Sulfur Dioxide and Nitrogen Oxides Emissions Trends - National Totals, 1900 - 2030

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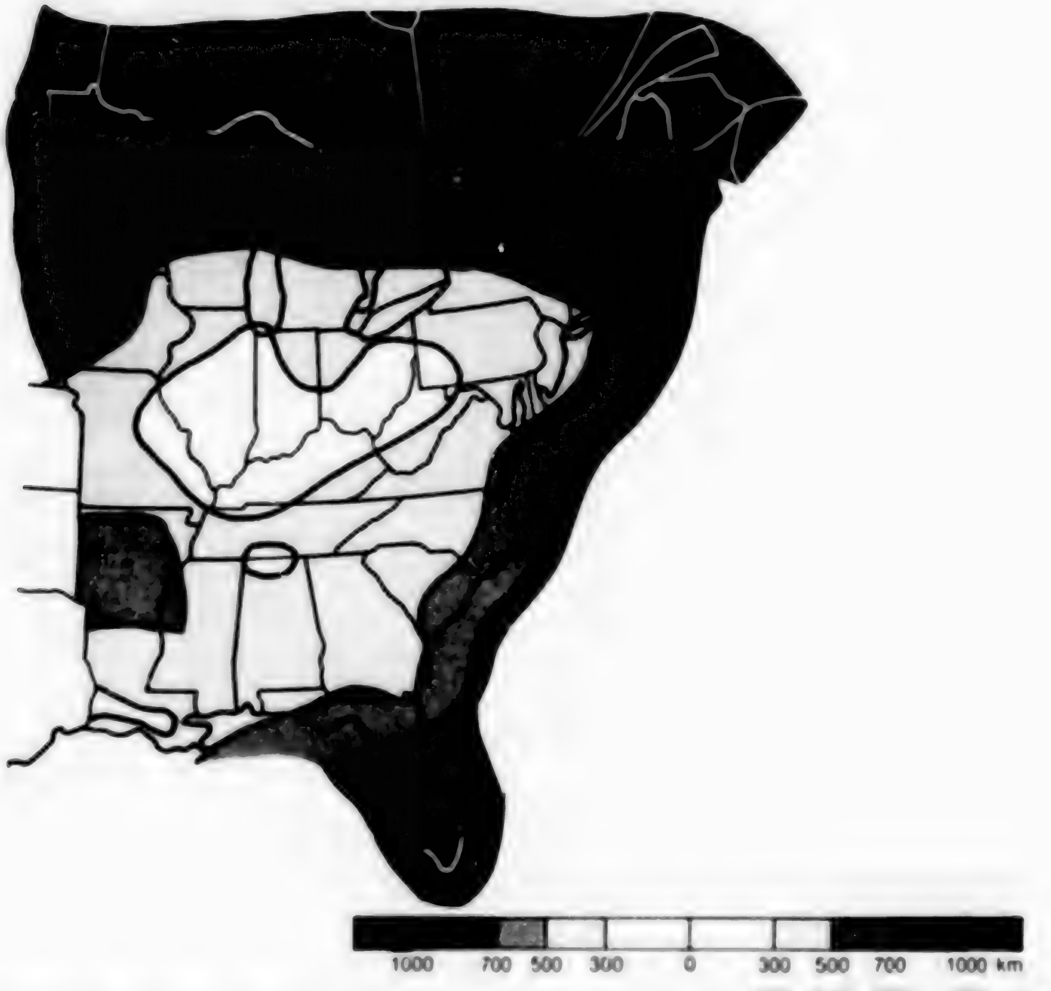
Because pollution sources are unevenly distributed across the Eastern United States and Canada, the relative contribution of emissions from local, midrange, and distant sources varies by region. As shown in Figure 4, sulfur deposition in the Midwest -- a region with high emissions -- is dominated by emissions from sources within 300 km (J. Shannon, Argonne National Laboratory; pers. comm.). The sulfur compounds that reach the less-industrialized New England region typically have traveled farther. The "average" distance -- considering the contribution from both local and distant sources -- is about 500 to 1,000 km.



The map above displays the "average" distance between the sources of sulfur dioxide emissions and the regions in which the sulfur compounds are eventually deposited. For each region of the Eastern United States and Canada, estimates of the sulfur deposited from all local, midrange, and distant emission sources are averaged to produce this map of typical transport distances. Such model-generated maps illustrate general patterns which will vary somewhat from year to year and model to model.

SOURCE: Jack Shannon, Argonne National Laboratory, 1984

Figure 4. Average sulfur transport distances across eastern North America.

OTA's analysis of acid deposition and other transported air pollutants concludes that these substances pose substantial risks to American resources. OTA estimates that thousands of lakes and tens of thousands of stream miles in the Eastern United States and Canada are vulnerable to the effects of acid deposition. Some of these have already been harmed. Elevated levels of atmospheric ozone have reduced crop yields on American farms by hundreds of millions of bushels each year. Acid deposition may be adversely affecting a significant fraction of Eastern U.S. forests; it, along with such other stresses as ozone and natural factors such as drought, may account for declining forest productivity observed in parts of the East. Both sulfur oxides and ozone can damage a wide range of manmade materials. Airborne fine particles such as sulfate reduce visibility and have been linked to increased human mortality in regions with elevated levels of air pollution.

Because this symposium is concerned primarily with fisheries, I will present OTA's analysis of aquatic effects before addressing legislative considerations. This paper will not address the dozen or so other segments of the 4 year study which encompassed natural resources at risk from transported air pollutants and economic sectors at risk from controlling these pollutants.

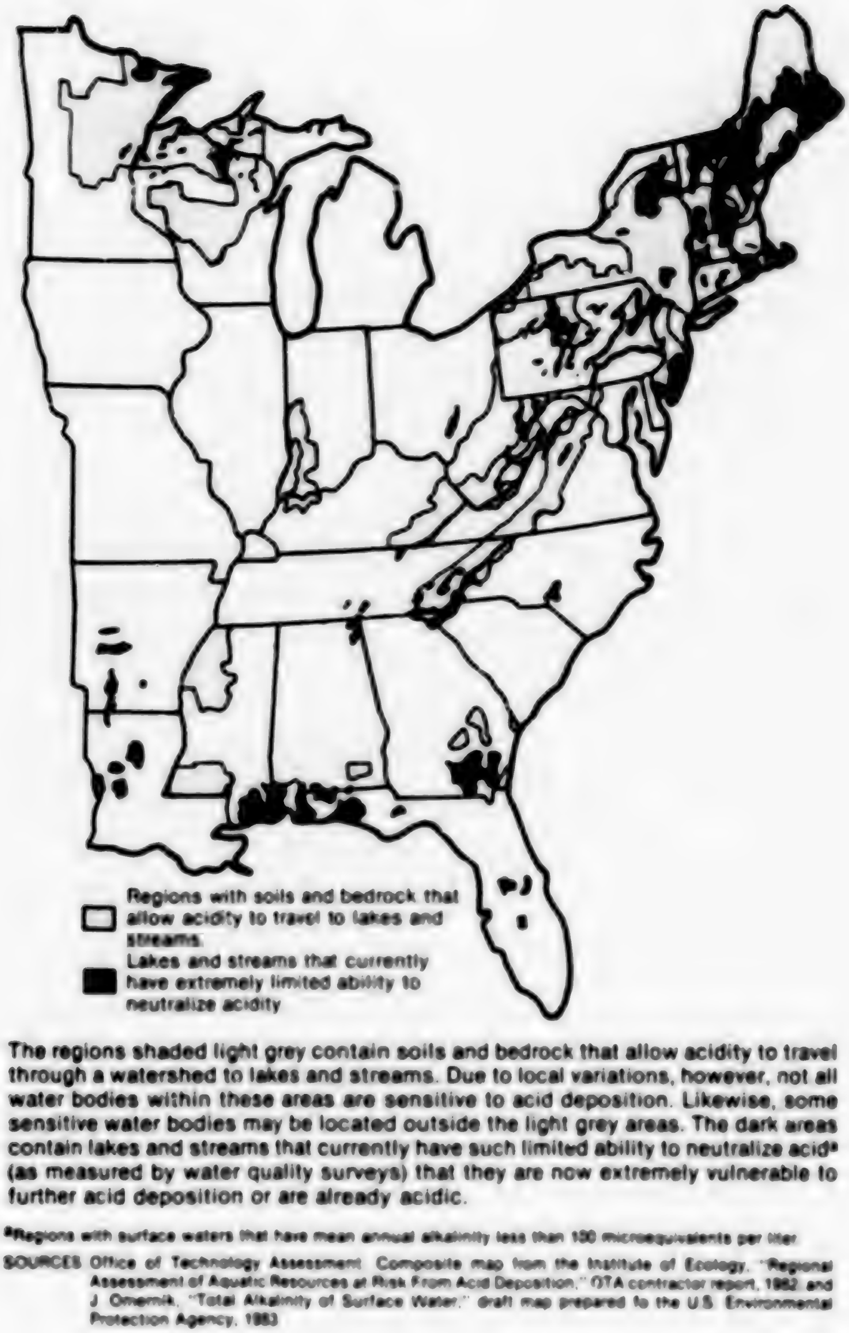
RISKS TO AQUATIC RESOURCES

By categorizing the predominant soil and geological characteristics in each county of the Eastern United States, OTA estimated the potential number of lakes and streams at risk from acid deposition. In the 31 states bordering and east of the Mississippi River, roughly 25 percent of the land area contains soils and bedrock that allow acidity to travel through the watershed to lakes and streams (see fig. 5). An OTA contractor (TIE, 1982) estimated that about 17,000 lakes and 112,000 miles of streams lie within these sensitive areas. Their study further estimated that about 3,000 lakes and 23,000 miles of streams -- or about 20 percent of those in the sensitive areas -- are now extremely vulnerable to further acid deposition or have already become acidic. New England has the greatest percentage of lakes and streams considered sensitive to acid deposition. The Upper Midwest also has large numbers of sensitive lakes, and many sensitive streams are found in the Central Appalachian region.

From existing historical records, acidification of only a small number of surface waters in North America can be documented; (Linthurst, 1982) data covering several decades are sparse. In the Adirondacks, researchers have further found correlations between increased acidity and decreased survival of fish in lakes and streams. Four other areas are known to have experienced actual loss of fish populations associated with surface water acidification: 1) the LaCloche Mountain region of Ontario, 2) Nova Scotia, 3) Southern Norway, and 4) Southern Sweden.

Acid deposition may not be the sole cause of these changes. However, large numbers of acidified and extremely sensitive lakes and streams are located in regions currently receiving the highest levels of acid deposition.

Though the economic value of these particular sensitive resources cannot be estimated, the Fish and Wildlife Service estimates that 21 million people


☐ Regions with soils and bedrock that allow acidity to travel to lakes and streams.
■ Lakes and streams that currently have extremely limited ability to neutralize acidity

The regions shaded light grey contain soils and bedrock that allow acidity to travel through a watershed to lakes and streams. Due to local variations, however, not all water bodies within these areas are sensitive to acid deposition. Likewise, some sensitive water bodies may be located outside the light grey areas. The dark areas contain lakes and streams that currently have such limited ability to neutralize acid[a] (as measured by water quality surveys) that they are now extremely vulnerable to further acid deposition or are already acidic.

[a] Regions with surface waters that have mean annual alkalinity less than 100 microequivalents per liter.

SOURCES: Office of Technology Assessment. Composite map from the Institute of Ecology, "Regional Assessment of Aquatic Resources at Risk From Acid Deposition," OTA contractor report, 1982, and J. Omernik, "Total Alkalinity of Surface Water," draft map prepared for the U.S. Environmental Protection Agency, 1983.

Figure 5. Regions of the Eastern United States with Surface Waters Sensitive to Acid Deposition

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spent $6.3 billion on all recreational freshwater fishing activities in the Eastern United States during 1980. One local-scale study (Menz and Mullen, 1984) estimated losses of approximately $1.7 million annually (1982 dollars) to New York resident anglers from lost fishing opportunities in 200 acidified Adirondack lakes and ponds. Potential losses to individuals whose livelihoods depend on the recreational fishing industry were not estimated. On a regional scale, the states at greatest economic risk are those with: 1) the greatest numbers of sensitive lakes, 2) the highest levels of acid deposition, and 3) the highest relative expenditures for recreational fishing. Among these are the New England states of Maine, Vermont, and New Hampshire; the Appalachian region of West Virginia and eastern Kentucky; and parts of the Midwestern states of Wisconsin and Minnesota.

CHOICES FACING THE CONGRESS

Current understanding of transported air pollutants allows scientists to describe potential resource damage (not only to lakes and streams, but also crops, forests, soils, materials, visibility, and human health) and the regions of the United States most susceptible to damage. But we cannot precisely quantify what levels of damage have already occurred or could occur in the future.

The costs of alternative control strategies, and who would bear these costs, can be described with more accuracy. But the benefits we'll get for those substantial costs, cannot be calculated with confidence.

Most current legislative proposals to control acid deposition would cost about $3 billion to $6 billion per year. Adding these new emissions control proposals to our Nation's current environmental laws would increase the total costs of environmental regulation by about 5 to 10 percent. Average electricity costs would rise by several percent -- as high as 10 to 15 percent in a few Midwestern states under the most stringent proposals. Additional emissions controls could also have important indirect effects, such as job dislocations among coal miners and financial burdens on some utilities and electricity-intensive industries.

Given the difficulty of quantifying the relationship between reducing emissions and preventing resource damage, Congress must base near-term policy decisions on the risk of resource damage, the risk of unwarranted control expenditures, and the distribution of these risks among different groups and regions of the country.

A variety of proposals has been introduced to address acid deposition in the 97th and 98th Congresses. Some bills call for a multi-faceted approach to transported pollutant problems such as accelerating the federal research effort and funding mitigation of the effects of acid deposition on acid-altered bodies of water. (Lake liming is the only measure currently supported by the Administration to immediately address acid deposition. A few million dollars has been set aside for this purpose during fiscal year 1985). Most of the bills proposing direct action would establish a 31-state or 48-state control region, and required reductions in annual sulfur dioxide emissions ranging from 8 million to 12 million tons below actual 1980 emissions levels by some point in the early 1990's.

DESIGNING A CONTROL PROPOSAL

Let's examine the considerations that go into designing an acid rain control bill by looking at 8 key decisions that must be made.

DECISION 1: WHICH POLLUTANTS SHOULD BE FURTHER CONTROLLED?

Sulfur dioxide and nitrogen oxides are major contributors of acidity to the environment. In the eastern U.S., sulfur compounds are responsible for about two times more acidity in precipitation than nitrogen compounds. Moreover, during most times of the year, much of the deposited nitrogen is removed by plants for use as a nutrient. Sulfur compounds, therefore, become responsible for an even greater share of acidity reaching water bodies. If NO_x emissions continue to increase, they will play a larger role in acidification. Nonetheless, SO_2 remains the most logical choice for initial control.

DECISION 2: HOW WIDESPREAD SHOULD A CONTROL PROGRAM BE?

Three regions are potential candidates (see fig. 6): 1) the approximately 21-state region receiving the greatest levels of acidity (i.e., precipitation acidity lower than pH 4.5); 2) a 31-state region (all states east of and bordering the Mississippi River) incorporating a band of states around the region of greatest deposition; 3) the continental 48 states.

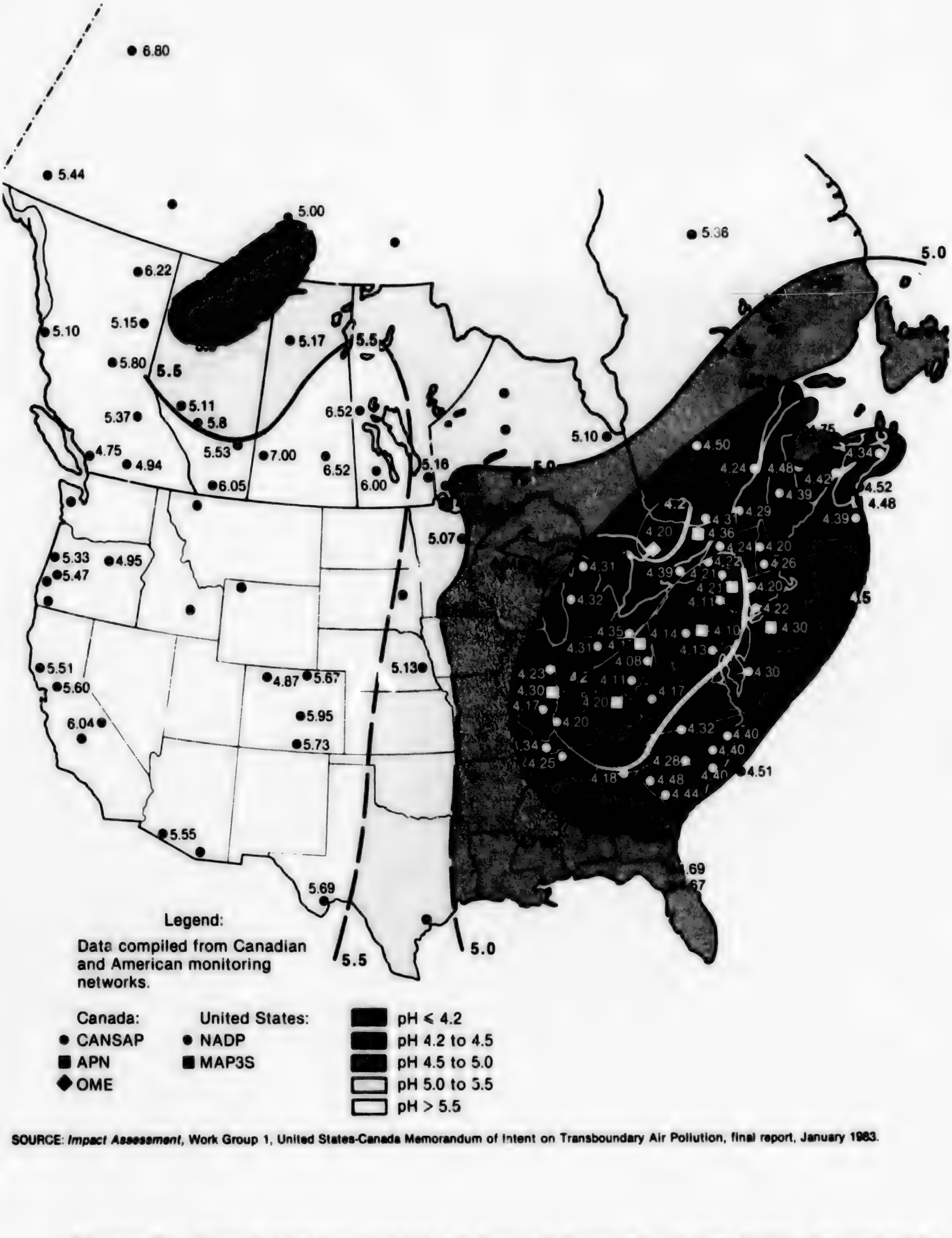
DECISION 3: HOW SHOULD THE LEVEL OF EMISSIONS REDUCTIONS BE SET?

Two types of strategies are available for choosing a socially desirable level of emissions reductions: 1) define a level of resource protection; and 2) decide how much to spend.

Unfortunately, environmental targets are difficult to come by. As an example, Congress could set a goal of protecting all but the most sensitive aquatic resources. The National Research Council (1981) reported no lakes are acid in areas where pH rain is greater than 4.6. Eliminating 8 to 10 million tons of sulfur dioxide emissions (a 35-45 percent reduction) in the eastern U.S. might achieve this goal in many areas receiving high levels of acid deposition, but probably would not do so in those areas receiving the greatest amounts (see fig. 7). Using another reference point, Congress could decide, for example, that $1 billion per year is an appropriate control cost to reduce the risks of damage to sensitive resources, given current uncertainties about the level of benefits to be gained. About 2 to 5 million tons of sulfur dioxide can be eliminated for this amount.

DECISION 4: BY WHAT TIME SHOULD REDUCTIONS BE REQUIRED?

Realistically, a Congressional decision to require further controls is likely to take 6 to 10 or more years to implement from the day of decision. Smaller levels of emissions reductions that require only minimal capital investment might be achieved somewhat more quickly.



SOURCE: *Impact Assessment*, Work Group 1, United States-Canada Memorandum of Intent on Transboundary Air Pollution, final report, January 1983.

Figure 6. Precipitation Acidity - Annual Average pH for 1980, Weighted by Precipitation Amount

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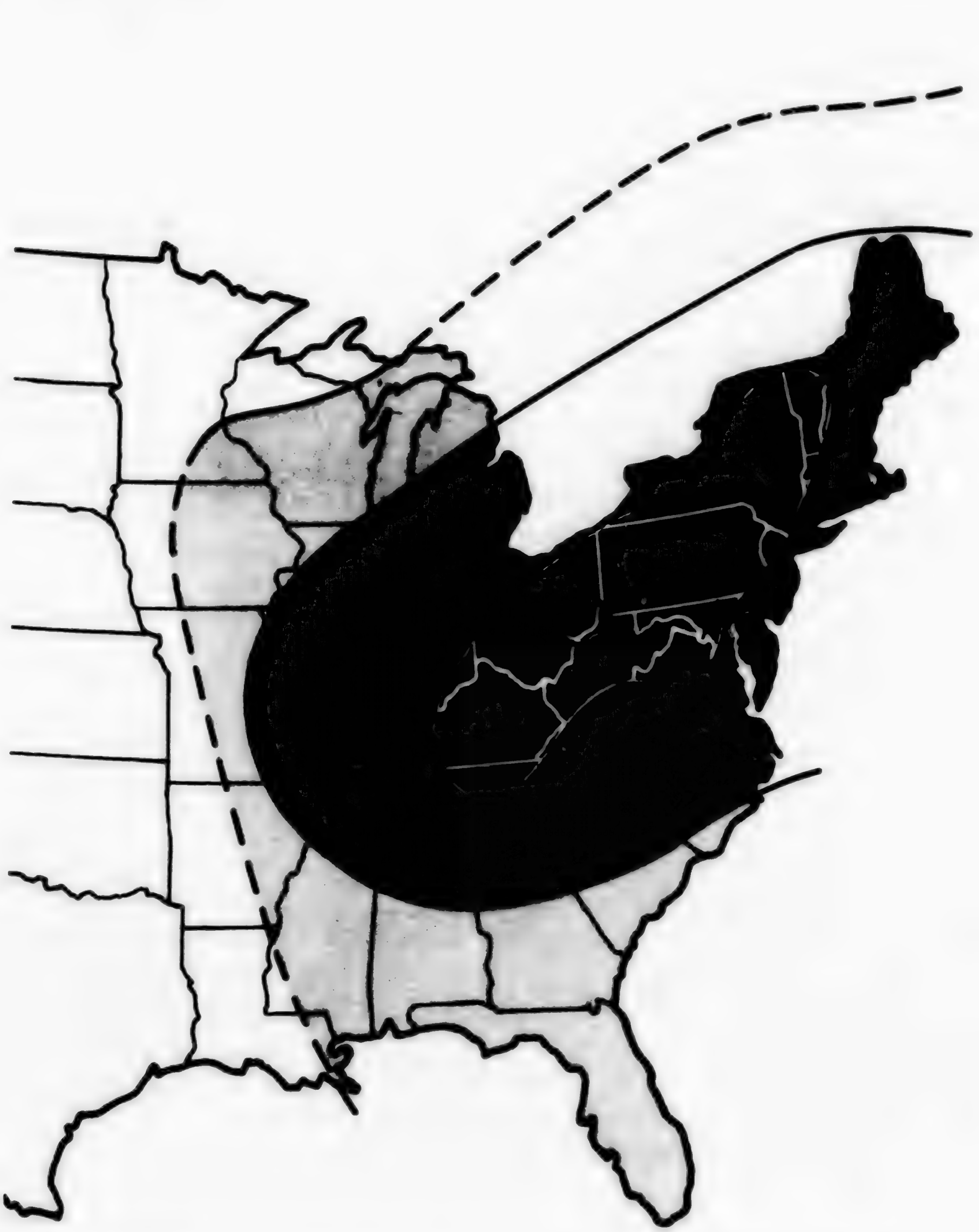


Estimated percent reduction in wet sulfate deposition necessary to increase pH to 4.6 or greater (1980 data).

Key:

☐ 0-30% reduction
▨ 30-50% reduction
■ 50-70% reduction
■ ≥ 70% reduction
— — limited data

SOURCE: Office of Technology Assessment.

Figure 7. Target Value: Average Precipitation pH of 4.6

DECISION 5: WHAT APPROACH TO CONTROL SHOULD BE ADOPTED?

Existing environmental regulatory approaches are most often either 1) receptor-oriented, i.e., setting goals or standards for exposure to pollutants; or 2) source-oriented, i.e., directly regulating total emissions or emission rates from sources or regions.

The first approach requires a well-developed understanding of the transport, transformation, fate, and effects of pollutants. Such knowledge -- accurate enough for regulatory purposes -- does not yet exist for acid deposition. A source-oriented approach could be implemented now, either by directly limiting emissions or emissions rates or by specifying the use of control technologies.

DECISION 6: HOW SHOULD EMISSIONS REDUCTIONS BE ALLOCATED?

Allocation formulas can take many different forms. For example, emissions could be reduced by an equal percentage in each state regardless of whether the state is a relatively high or low emitter. Alternatively, allowable emission rates could be set, requiring the greatest reductions from sources that emit the greatest amounts of pollution per unit of fuel burned (or similar measure). A formula could be based on utility emissions alone or statewide total emissions. Allocation formulas differ in their resulting geographic patterns of emissions reductions and administrative complexity.

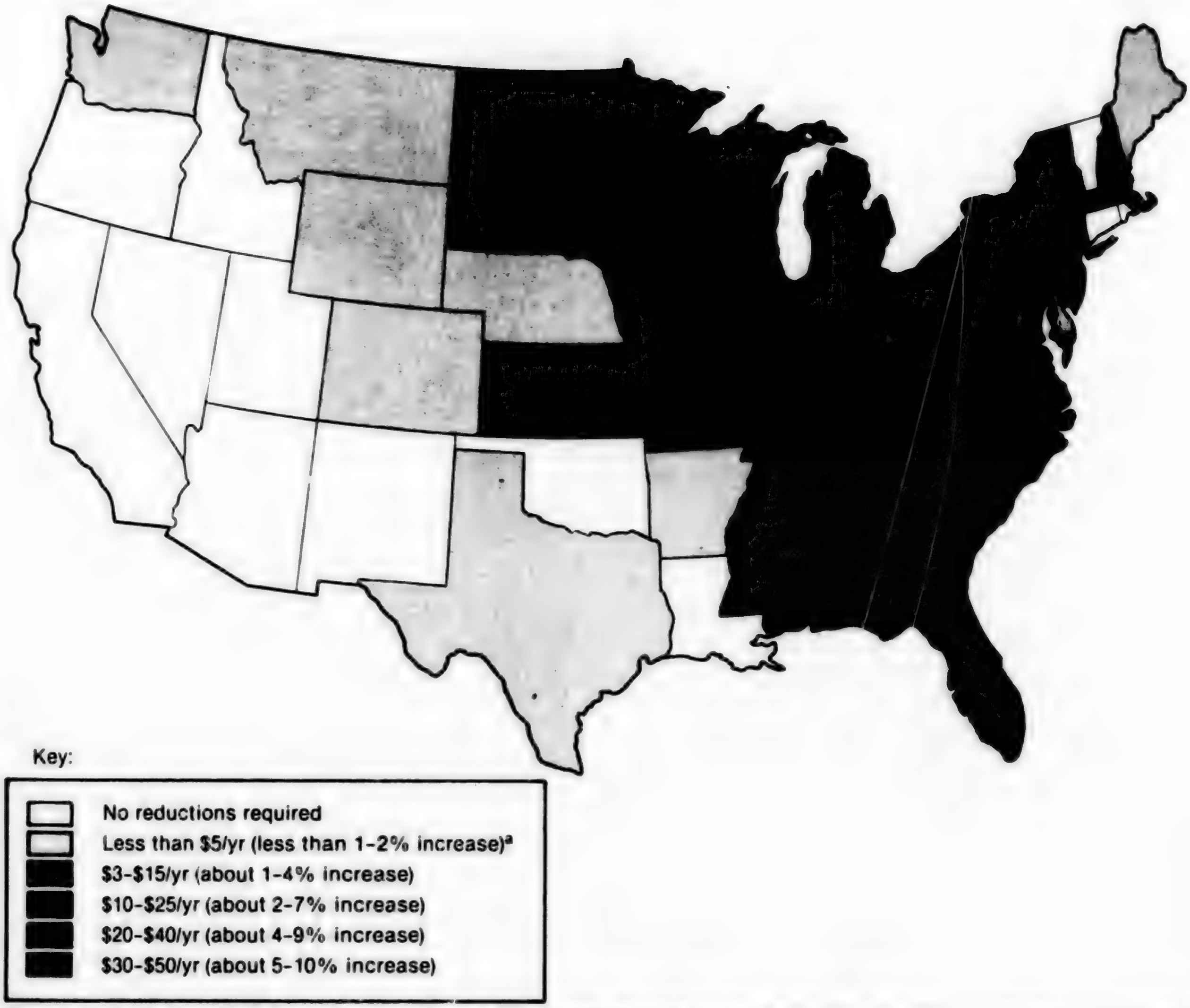
DECISION 7: WHO SHOULD PAY THE COSTS OF EMISSIONS REDUCTIONS?

Allocating emissions reductions and allocating the cost of those reductions are two distinct issues. Congress could decide that 1) the full costs of control should be paid by the sources required to reduce emissions, the traditional "polluter pays" principle, or 2) control costs should be funded by a group larger than those required to reduce emissions through a tax or similar plan on the grounds that it is difficult to determine culpability.

DECISION 8: WHAT CAN BE DONE TO MITIGATE UNDESIRABLE EFFECTS OF A CONTROL POLICY?

Legislated reductions in sulfur dioxide emissions are most likely to affect two economic sectors: the coal industry and the electric utility industry. If emitters are allowed to switch to lower sulfur fuels, often a relatively less expensive means of reducing emissions, some coal production will shift from high-sulfur to low-sulfur coal producing regions. OTA estimates that there would be 20,000 to 30,000 fewer jobs for high-sulfur coal miners under the more stringent control proposals. This might be mitigated by requiring the use of specific control technologies, e.g., scrubbers, that allow the use of high-sulfur coals yet still meet emissions reductions requirements; however, mandating control technology could raise costs of a control program by 25-50 percent. Special compensation to workers or communities affected by the new law would also be possible.

Figure 8 shows the economic impacts of a proposed 10 million ton reduction where the polluter pays. Such impacts could be spread out more evenly by taxing all electricity produced and using the revenues generated to fund clean-up.


Key:
No reductions required
Less than $5/yr (less than 1-2% increase)[a]
$3-$15/yr (about 1-4% increase)
$10-$25/yr (about 2-7% increase)
$20-$40/yr (about 4-9% increase)
$30-$50/yr (about 5-10% increase)

[a] Average annual cost increase (1982 dollars) for a typical residence consuming 750 kWh/month electricity. Percentage rate increases in each State are calculated from State-average 1982 electricity costs (ranging from about $200 to $900/yr; United States average about $600/yr)

SOURCE: Office of Technology Assessment, based on analyses by E. H. Pechan & Associates, Inc.

Figure 8. Cost of Reducing Sulfur Dioxide Emissions by 10 Million Tons per Year, Nationwide Increases in Annual-Average Electricity Bills for a Typical Residential Consumer

Congress can specify a control program by considering each of the eight "decision areas" I just summarized. Obviously, many alternatives are possible. There is a continuum of available choices ranging from modest, interim reductions to large-scale control programs. Each strikes a different balance between the risks of future resource damage and the risks of an inefficient program.

RECENT LEGISLATIVE PROPOSALS

Table 1 includes a brief description of the acid deposition related bills that were introduced during the 98th Congress. Included are bills that proposed emissions reductions, continued research, and liming. Bills that proposed emissions reductions are divided into two categories: 31-State and 48-State approaches. The description following each bill number includes: the pollutants to be controlled, the magnitude of emissions reductions, as well as several other aspects of the eight key decisions described above.

I'll describe one of these control proposals in a bit more detail, the rather complex Sikorski-Waxman bill (H.R. 3400) which had over 100 sponsors in the 98th Congress. It would require a 10 million ton reduction (about 38%) in the sulfur dioxide emissions and a 4 million ton reduction in nitrogen oxides by 1993. The control region is the 48 contiguous states. NO_x reductions would be achieved by setting new emission rate limits for utilities as well as trucks. SO_2 reductions would be allocated to states on the basis of 1980 utility emission rates. (Inventories of utility emissions are considered more accurate than for industries, hence the former serves as a better baseline). Allocating reductions on emission rates -- pounds of SO_2 per million Btu of energy consumed -- is generally a less expensive approach than requiring all states to reduce by a set percentage. For example, states with high emission rates can achieve significant reductions by washing coal, or fuel switching.

But fuel switching -- a cheap alternative in many cases -- eliminates high-sulfur coal mining jobs in the East. To alleviate this undesirable effect of a control policy, H.R. 3400 specifies that the 50 plants emitting the most SO_2 (and at a rate greater than 3 lbs/million Btu) must use technology (e.g., scrubbers) to achieve their reduction. These 50 plants will account for about 6.5 million of the total 10 million tons SO_2 reduction sought; with the incentive for fuel-switching removed, most of the high-sulfur coal market would remain intact. Because the cost of scrubbers is high, a tax of 1 mill per kilowatt hour is levied on non-nuclear generated electricity produced in the continental United States to pay for 90 percent of the capital cost of installing these scrubbers. This tax would alleviate some of the utility expenditure for the mandated technology.

This bill represents one possible set of answers to the eight generic questions key to the design of an emissions reduction proposal. It seeks emissions reductions by 1993 that will not overshoot the National Academy of Sciences recommendation of 50 percent, spreads the costs and the actual reductions to 48 states, attempts to protect coal miners, and helps utilities finance scrubbing through a tax on electricity production.

With over 100 sponsors, this bill is definitely a serious contender in the House of Representatives. However, it is still a long way from having the votes of the 218 Congressmen and 51 Senators needed to pass it.

More than 20 other permutations of acid deposition control bills have been proposed over the last sessions of Congress. How the three-fold dilemma of scientific uncertainty, differing values, and distributional concerns will be ultimately resolved remains unclear. However, I hope I've given you a clearer understanding of the constraints, compromises and conundrums Congress faces as it seeks to address the issue of transported air pollutants.

Table 1. Acid Deposition Related Bills of the 98th Congress

Bill	Sponsor(s)	Proposed Action
Research/Liming		
S. 454	Byrd, 16 cosponsors	Report after 5 years; mitigation funds
H.R. 1405	Rahall, 77 cosponsors	Report after 5 years; mitigation funds
S. 766	Randolph, 1 cosponsor	Report after 5 years; mitigation funds; no SIP revisions
H.R. 3904	Donnelly, 20 cosponsors	Funds to restore water quality
EMISSIONS REDUCTIONS -- 31 states		
S. 2215	Glenn	SO_x: 8 million below 1980; restrictions on fuel switching; elec. tax pays for control tech (3 mills)
S. 768 as amended	Senate Committee on Environment & Public Works	SO_x: 10 million below 1980; NO_x: no rate increases, truck standards
H.R. 3251	D'Amours, 10 cosponsors	SO_x: about 10 million below future; 2 for 1 NO_x/SO_x trade
S. 145	Mitchell, 17 cosponsors	SO_x: 10 million below 1980; NO_x: 1980 ceiling; 2 for 1 NO_x/SO_x trade
H.R. 2794	St Germain	SO_x: 10 million below 1980; NO_x: 1980 ceiling; 2 for 1 NO_x/SO_x trade
S. 2001	Durenberger, 3 cosponsors	SO_x: 10 million below 1980; NO_x/SO_x tax raising $40 billion
H.R. 132	Gregg, 42 cosponsors	SO_x: 10 million beloe 1980 SIP/actual; NO_x: 1980 ceiling; 2 for 1 NO_x/SO_x trade
H.R. 5370	Udall, 27 cosponsors	SO_x: 11 million below 1980; "best available control technology" for SO_x and NO_x after 1996

Table 1 concluded. Acid Deposition Related Bills of the 98th Congress

Bill Research/Liming	Sponsor(s)	Proposed Action
S. 769	Stafford, 5 cosponsors	SO_x: 12 million below 1980; NO_x: 1980 ceiling; 2 for 1 NO_x/SO_x trade
H.R. 3400	Sikorski/Waxman, 128 cosponsors	SO_x: 10 million below future levels, control tech on "top 50" plants; NO_x: NSPS and truck standards; non-nuc. elec. tax (1 mill) pays for control tech
H.R. 5970	Vento, 3 cosponsors	similar to H.R. 3400, some changes in control tech funding
H.R. 5794	Eckart, 3 cosponsors	SO_x: 10 million below future levels, control tech on most plants; NO_x: NSPS and truck standards; non-nuc. elec. tax (1.3 mill) pays for control tech
H.R. 5590	Green	SO_x: 10 million below 1980, repeals NSPS percentage reduction requirement; NO_x: NSPS and truck standards
H.R. 4906	Rinaldo, 9 cosponsors	SO_x: about 10.5 million below 1980; NO_x: NSPS and truck standards; fossil elec. tax (1.5 mill) returned to States
H.R. 4404	D'Amours, 30 cosponsors	SO_x: 12 million below future levels, control tech on "top 50" plants; NO_x: NSPS and truck standards; fossil elec. tax (1.5 mill) returned to States
H.R. 4483	Aspin	tax on coal sulfur ($.50/lb sulfur); pays for control tech

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FACTORS CONTRIBUTING TO THE COMPLEXITY OF THE ACID PRECIPITATION SURFACE WATER ACIDIFICATION PROBLEM

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FACTORS CONTRIBUTING TO THE ACID PRECIPITATION-SURFACE WATER ACIDIFICATION PROBLEM

Despite the abundant discussion (both technical and political) of the phenomenon of acidic deposition, the issues are still in the process of being defined scientifically as to the mechanisms of acidification of surface waters and effects of terrestrial systems. Anthropogenic atmospheric contributions to a naturally acidic atmospheric system having an antiquity of two billion years have been focused on almost to the exclusion of the natural system and its components and reactions. Similarly, acidic atmospheric contributions from anthropogenic sources have been the principle focus of terrestrial investigations, again largely ignoring the concurrent natural and other man-influenced reactions in terrestrial geochemical systems. In fact, a number of processes in atmospheric and terrestrial systems are dynamically coupled and vary both spatially and temporally, increasing the difficulty of studying them. For example, changes in land-use that result in increased forest soil humus, when concurrent with long-term climatic changes that increase the flushing of such acid soils by larger volumes of throughflow, would parallel what have been indicated as increased anthropogenic atmospheric deposition in acidification of surface waters. The scientific understanding of such complex interrelationships must be increased substantially before effective management of the hydrogeochemical systems can be achieved. At present, the scientific data and understanding for adequate management are emerging much more slowly than are proposed political solutions to the problem.

DETECTING REGION-WIDE TRENDS IN SURFACE WATER QUALITY

by

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DETECTING REGION-WIDE TRENDS IN SURFACE WATER QUALITY

Studies of individual stations in the Northeast reveal long-term changes in chemical concentrations which may be related to acid deposition. Studies of populations of stations, such as the Adirondack Mountain lakes, indicate that acidification has occurred over the selected region, but since only end-members of a temporal change are known, the temporal pattern of change is unknown. By combining data from a large number of water quality sampling stations, it is possible to evaluate temporal patterns for geographically large regions. Because it is impractical to evaluate in great detail the quality of data from each of thousands of stations, patterns observed from analysis of such a large data set need to be confirmed by comparing them to patterns observed for more thoroughly examined stations. This multi-layered approach has the advantage of providing both the regional generality of a statistically based analysis, with a means of increasing verification of the patterns observed.

BIOGEOGRAPHIC INFLUENCES, SPECIES INTERACTIONS AND LAKE ACIDIFICATION

by

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INTRODUCTION

Relating changes in fish communities to acidification requires a knowledge of community composition prior to acid inputs. In regions where historical fishery data are sparse or only available for a few lakes or selected species, comparative biogeographic studies can be used to predict fish community characteristics from readily available limnological data. For example, species-lake area relations have been used to estimate the number of fish populations that have become extinct in regions receiving acid deposition (Harvey and Lee 1982; Somers and Harvey 1984). The approach has been to develop, by using non-acidified lakes, a regression equation that predicts species richness as a function of lake size. This equation is then used to estimate the number of species that would be expected in lakes prior to acidification. Subtracting the observed from the expected number of species in each lake and summing across all acidified lakes provides an estimate of the number of fish populations lost in the region. A potential problem with this approach is the assumption that species-area relations for the non-acidified lakes (which typically have high alkalinity) and acidified lakes (which presumably had low alkalinity) were similar before acidification. If they were not, and if low-alkalinity lakes always had fewer species than high-alkalinity lakes of similar size, then using the species-area relationship for non-acidified (high-alkalinity) lakes to predict species richness in acidified (low-alkalinity) lakes will result in an overestimate of species losses related to cultural acidification. Using data from 100 Wisconsin lakes, I examine the likelihood that such overestimates will occur.

Biogeographic analyses have also been used to identify abiotic factors which influence species distributions. For example, Wisconsin lakes that differed in vulnerability to acidification also had different fish communities (Rahel and Magnuson 1983). However, because these lakes differed in several biogeographic and physical/chemical attributes, it was difficult to determine which factors most influenced species distributions. Below, I examine the roles of lake size, isolation and alkalinity in structuring fish communities in northern Wisconsin lakes.

METHODS

Fish species lists, along with morphometric and limnological data, were assembled for 100 lakes in north-central Wisconsin (Rahel 1982). All lakes had summer pH values above 5.0, did not become anoxic in winter, and were not encircled by a bog mat. Recent evidence indicates that these lakes have not been affected by cultural acidification (J.J. Magnuson, University of Wisconsin, Madison, Wisconsin, pers. comm.). Because sampling effort varied among lakes, only presence/absence data were used. Water chemistry measurements were from samples collected just below the surface during summer. Further details on sampling procedures are given by Rahel and Magnuson (1983).

To determine the appropriateness of using the species-area relationship for high-alkalinity lakes to predict species losses in low-alkalinity lakes, I divided the 100 Wisconsin lakes into high- and low-alkalinity groups and compared species-area regressions. A value of 10 mg/L (as $CaCO_3$) was used to separate high- and low-alkalinity lakes because it is near the boundary used to define vulnerability to acidification (Glass 1980). Analysis of covariance was used to determine if the two regression equations had equal slopes and intercepts. The error that might occur if an inappropriate species-area regression was used to predict fish species losses in acidified lakes was simulated by assuming that all low-alkalinity lakes would become acidified. Various species-area regressions were then used to estimate expected fish species richness in these lakes. The observed number of species was then subtracted from the predicted number to estimate the accuracy of these regression equations in predicting fish species richness in low-alkalinity Wisconsin lakes.

To examine the roles of lake size, alkalinity, and isolation in structuring fish assemblages, I partitioned the 100 lakes into four categories on the basis of morphometric and limnological characteristics (Table 2). Group I consisted of large (greater or equal to 80 ha), high-alkalinity (> 10 mg/L as $CaCO_3$), drainage lakes (i.e., lakes with inlet and outlet streams). These lakes would be least sensitive to acidification because of their high acid-buffering capacity. They would be expected to have a diverse fish fauna by virtue of their large size, high biological productivity, and connections to other aquatic habitats (Magnuson 1976). Group II consisted of small (<80 ha), drainage lakes having high alkalinity. Lakes in group II differed from those in group I mainly in size, and should therefore lack species restricted to large bodies of water. Lakes in group III were similar to those of group II in size and alkalinity but were seepage lakes (i.e., lakes without inlet or outlet streams). These seepage lakes would be expected to lack species that reproduce in streams. Group IV consisted of small, low-alkalinity seepage lakes that were most vulnerable to acidification and had a depauperate fish community dominated by centrarchids and yellow perch (Rahel and Magnuson 1983; Wiener et al. 1983). Ten lakes did not fit into any of the four groups and were not used in this analysis. Other lake types (e.g., small, low-alkalinity, drainage lakes), are uncommon in Wisconsin.

RESULTS AND DISCUSSION

SPECIES-AREA RELATIONS

Northern Wisconsin lakes with high alkalinity had more fish species than low-alkalinity lakes of similar size (Fig. 9). The slope of the species-area regression was greater for high-alkalinity lakes compared to low-alkalinity lakes ($p = 0.10$ ANCOVA). Although most of the low-alkalinity lakes are also small and lack tributary streams, the relationship between alkalinity and species richness appears to be a general one. Two large, low-alkalinity lakes fall along the same species-area regression line as small, low-alkalinity lakes. Furthermore, when only seepage lakes were compared, low-alkalinity lakes still had fewer species than high-alkalinity lakes (Wiener et al. 1984).

Given that lakes of different alkalinity have different species-area relationships, it would be inaccurate to use a species-area regression from high-alkalinity lakes to predict species richness in low-alkalinity lakes. For the Wisconsin lakes, the regression for high-alkalinity lakes overestimates species richness by an average of 5.2 species per lake for the

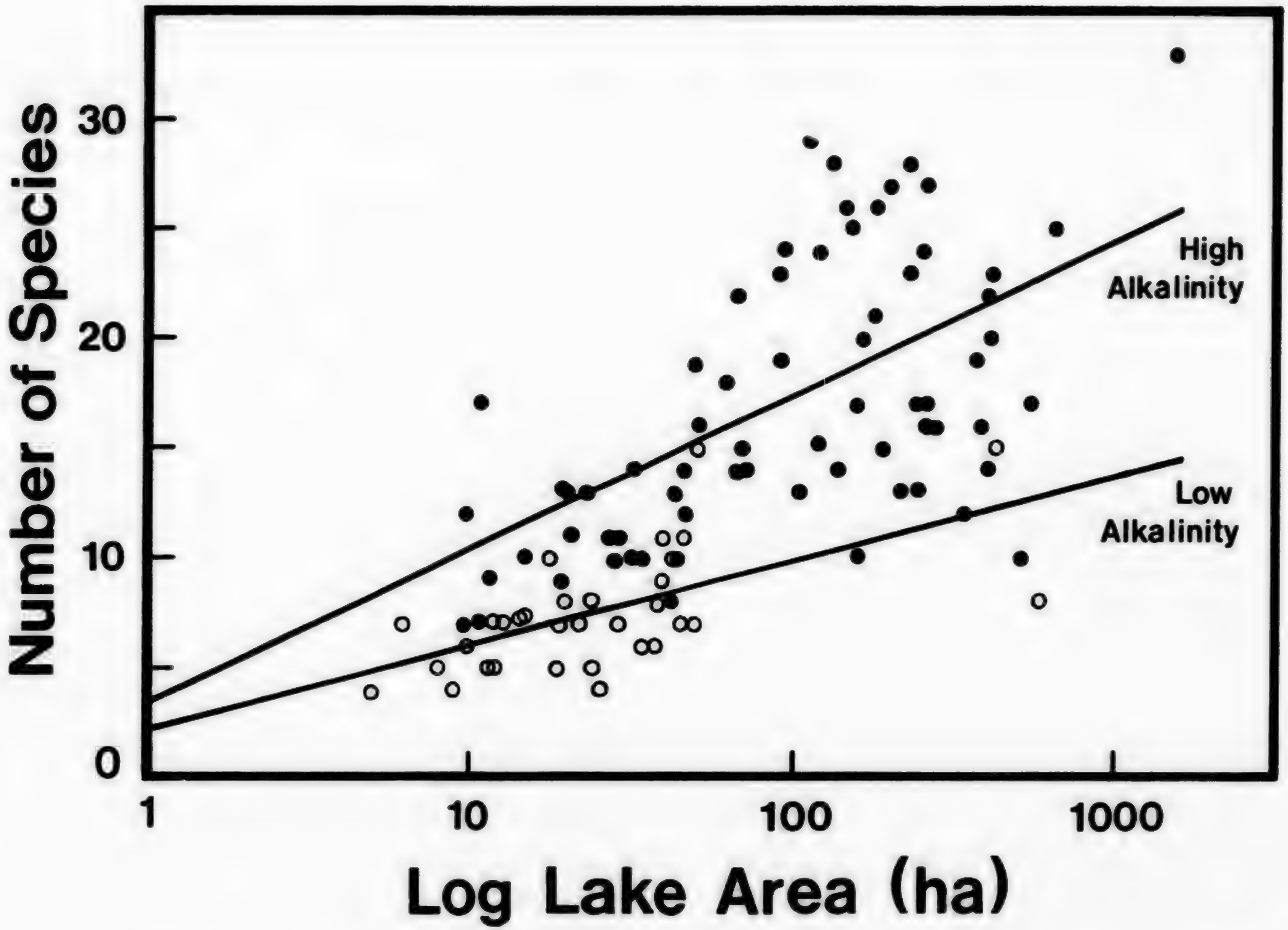

Fig. 9. Relationship between the number of fish species and $\log_{10}$ (surface area) for high-alkalinity (●) and low alkalinity (o) lakes in northern Wisconsin. The regression equation for the high-alkalinity lakes (>10 mg/L as $CaCO_3$) is $Y = 2.67 + 7.15 \log_{10}$ (area) ($n = 67$, $r^2 = 35$); for the low-alkalinity lakes (<10 mg/L as $CaCO_3$) it is $Y = 2.19 + 3.76 \log_{10}$ (area) ($n = 33$, $r^2 = 0.37$).

Table 2. Use of species-area regressions to predict fish species richness for 33 low-alkalinity (≤ 10 mg/L as $CaCO_3$), northern Wisconsin lakes. All lakes were from the 100-lake data set discussed in the text.

Regression model	r^2	Number of species-populations for 33 low-alkalinity lakes	Number of excess species-populations predicted for the 33 lakes[b]	Average number of excess species-populations per lake
Regression model based on 67 high-alkalinity lakes[a]				
$Y= 2.67 + 7.15 \log_{10}$ (area)	0.347	414	170	5.2
$Y= 1.76 + 7.20 \log_{10}$ (area) $+ 0.57 \log_{10}$ (alkalinity)	0.348	391	147	4.5
Regression model based on all 100 lakes				
$Y= -1.75 + 8.68 \log_{10}$ (area)	0.496	338	94	2.8
$Y= -2.65 + 7.14 \log_{10}$ (area) $+ 3.39 \log_{10}$ (alkalinity)	0.578	271	27	0.8

[a] alkalinity > 10 mg/L as $CaCO_3$

[b] number predicted minus the 244 species-populations present in the 33 lakes

33 low-alkalinity lakes (Table 2). If acidification were to eliminate fish populations in the low-alkalinity Wisconsin lakes, this approach would overestimate by 170 (414 predicted - 244 actual) the number of populations that became extinct. One remedy might be to include an alkalinity term in a multiple regression model. However, this did not greatly improve the model because alkalinity was not strongly related to the number of fish species when only alkaline lakes (>10 mg/L as $CaCO_3$) were used to develop the regression equation (Table 2). An average of 4.5 excess species per lake would still be predicted. A model based on the species-area relationship for all 100 lakes (including high- and low-alkalinity lakes) improved the prediction, and addition of an alkalinity term resulted in the best prediction of species richness (an average of 0.8 excess species per lake predicted for the 33 low-alkalinity lakes). Thus the best model for predicting species richness in low-alkalinity, northern Wisconsin lakes incorporated both lake area and alkalinity, and included at least some low-alkalinity lakes.

To determine if alkalinity might be a useful predictor of fish species richness in other lake districts, I examined the species-area-alkalinity regression for lakes near Wawa, Ontario. Somers and Harvey (1984) used the species-area regression for 34 of the lakes which appeared to have normal fish assemblages to predict species losses from 16 acidified lakes. Their model predicted species richness from the logarithm of lake area and accounted for 33.5% of the variation in species richness among lakes. Including an alkalinity term did not improve the regression (coefficient of determination remained .335) and the coefficient for the alkalinity term was not significantly different from zero. Furthermore, whereas the partial correlation between the number of fish species and the logarithm of alkalinity (after removing the effect of lake size) was significant for the 100 Wisconsin lakes ($r = .40$, $p < .01$), it was not significant for the 34 Wawa, Ontario lakes ($r = -.02$, $p = .91$). Contrary to results for the Wisconsin lakes, alkalinity was not a useful predictor of species richness in the Ontario lakes.

The degree to which alkalinity and other measures of lake productivity are useful predictors of fish species richness needs to be examined further. However, the existence of such a relationship in northern Wisconsin, central New York (Browne 1981), and Lake Memphremagog, Quebec-Vermont (Gascon and Leggett 1977), indicates that some measure of productivity should be considered when regression models, developed for one group of lakes, are used to predict species richness in lakes with different morphometric and limnological characteristics.

BIOGEOGRAPHIC FACTORS AND FISH COMMUNITY COMPOSITION

White suckers, largemouth bass, sunfish (Lepomis spp.), bullheads (Ictalurus spp.) and yellow perch were common across the entire range of lake size and alkalinity and were the major species represent in small, low-alkalinity, seepage lakes in northern Wisconsin (group IV, Table 3). Seepage lakes of similar size, but with higher alkalinity (group III), contained this core group of species plus mottled sculpin and several species of minnows and darters. These additional species seemed to be restricted to waters that had at least moderate alkalinity and a circumneutral pH. Based on evidence from laboratory bioassays, species distributions among naturally acidic lakes, and species losses from culturally acidified lakes, mottled sculpins and many minnows and darters appear to be intolerant of low pH. For example, minnows (Pimephales spp., Notropis spp.) and darters (Etheostoma spp.) were absent below pH 6.0 in naturally acidic Wisconsin lakes even when appropriate habitat was present (Rahel and Magnuson 1983). The sensitivity of these species to low pH has also been demonstrated in laboratory bioassays (Mount 1973) by field manipulations of pH (Mills 1984) and by distribution studies (Hastings 1979). Because of their intolerance of low pH, these species have probably always been absent from small, low-alkalinity lakes having pH values below 6.0. However, because these species were also absent from small, low-alkalinity seepage lakes with neutral pH, biotic interactions may have also been involved. The paucity of mottled sculpins, cyprinids, and darters in small, oligotrophic lakes has been attributed to both predation and competition from centrarchids and yellow perch (Tonn and Magnuson 1982; Rahel 1984).

The low frequency of occurrence of rock bass and northern pike in small, low-alkalinity, seepage lakes was not the result of acid-sensitivity, since both species are acid-tolerant (Harvey 1980). Reasons for the rarity of rock bass are unknown, but northern pike are probably limited by a lack of vegetated littoral areas needed for spawning (Becker 1983).

While minnows, darters, and mottled sculpin were probably absent from low-alkalinity, seepage lakes because of both direct and indirect effects of low pH and associated water chemistry conditions, the rarity of other species appears to be related to small lake size. Smallmouth bass, muskellunge, burbot, logperch, walleye and trout-perch were less common in small lakes than in large lakes (Table 3). Except for muskellunge, these species require wave-washed, hard-bottomed substrate as habitat or spawning sites (Becker 1983). Such habitat is limited in small lakes, which generally have little wave action. Burbot prefer cool, well-oxygenated water and would not be expected in small lakes that are warm due to polymixis or have cool water only in an anoxic hypolimnion during the summer.

Lake isolation appeared to have little effect on fish community composition. Small high-alkalinity lakes with inlet and outlet streams (group II, Table 3) had fish assemblages similar to those in small high-alkalinity lakes lacking such streams (group III). Redhorses occurred in a few small drainage lakes (group II), but not in small seepage lakes. These fish spawn in stream riffles and thus their absence from seepage lakes was likely related to a lack of access to appropriate spawning areas. Golden shiners were more common in small drainage lakes than in small seepage lakes and this may reflect the fact that inlet and outlet streams can provide a refuge for species that might otherwise be eliminated from lakes by predators or competitors. Moyle (1973) suggested that some minnow species thought to be competitively inferior persisted in a Minnesota lake because they could maintain a high population in a tributary stream.

Examining species composition in lakes partitioned on the basis of size, alkalinity, and isolation helps to clarify reasons for the absence of many fish species from small, low-alkalinity seepage lakes in northern Wisconsin. Previous conclusions that certain species were absent because of low pH (Rahel and Magnuson 1983; Wiener et al. 1984) still apply to darters of the genus Etheostoma and most cyprinid species. The rarity of other species now appears to also result from small lake size (e.g., muskellunge, burbot, logperch,

Table 3. Comparison of fish species composition among Wisconsin lakes differing in surface area, alkalinity and isolation. Values are the percent of lakes within a lake category that contain a given taxon. All lakes have summer pH's above 5.0 and are not anoxic in winter. Lakes most sensitive to acidification (Group IV) are small, low-alkalinity lakes lacking inlet/outlet streams.

Lake category Lake size[a] Alkalinity[b] Inlet/outlet	I Large High Present n = 33	II Small High Present n = 17	III Small High Absent n = 11	IV Small Low Absent n = 29
Taxa common in all lake types (% occurrence)				
Catostomidae				
White sucker	100	94	82	69
Centrarchidae				
Largemouth bass	88	82	82	86
Lepomis spp.	100	100	82	97
Ictaluridae				
Ictalurus spp.	85	82	91	59
Percidae				
Yellow perch	100	100	100	97
Taxa less common in small, low-alkalinity lakes than in other lake types				
Centrarchidae				
Rock bass	91	65	55	24
Cottidae				
Mottled sculpin	64	29	27	0
Cyprinidae				
Notropis spp.	85	41	36	0
Pimephales spp.	88	35	82	0
Esocidae				
Northern pike	100	88	55	34
Percidae				
Etheostoma spp.	82	53	64	0

Table 3 concluded.

Lake category Lake size[a] Alkalinity[b] Inlet/outlet	I Large High Present n = 33	II Small High Present n = 17	III Small High Absent n = 11	IV Small Low Absent n = 29
Taxa less common in small lakes in general				
Catostomidae				
Moxostoma spp.	55	24	0	0
Centrarchidae				
Smallmouth bass	85	18	55	21
Black crappie	85	88	55	38
Cyprinidae				
Golden shiner	82	82	36	34
Esocidae				
Muskellunge	88	35	18	3
Gadidae				
Burbot	67	12	18	0
Percidae				
Logperch	42	6	18	0
Walleye	100	47	64	21
Percopsidae				
Troutperch	33	0	0	0
Limnological variables[c]				
Lake size (ha)	284(88-1566)	38(10-72)	31(10-70)	22(5-47)
pH	7.1(6.3-8.6)	7.3(6.5-9.2)	7.2(6.7-8.1)	5.9(5.1-7.7)
Alkalinity (mg/L as $CaCO_3$)	28(15-67)	52(15-120)	24(12-52)	3(0-9)
Number of fish species	21(10-30)	13(7-22)	12(7-17)	7(4-11)

[a] Size categories are large (≥80 ha) and small (<80 ha).
[b] Alkalinity categories are high (>10 mg/L $CaCO_3$) and low (≤ 10 mg/L $CaCO_3$).
[c] All values are mean (range) except pH which is median (range).

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trout-perch, walleye) or the absence of tributary streams (e.g., redhorses). Another group of species is present across a wide range of lake size and alkalinity (white sucker, largemouth bass, sunfish (*Lepomis* spp.), bullheads (*Ictalurus* spp), and yellow perch). These habitat relations should be useful in predicting the fish community composition expected in other northern temperate lakes, and in determining if particular species are absent from acidified lakes because of low pH or other habitat limitations.

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AN EARLY LIFE STAGE BROOK TROUT (*Salvelinus fontinalis*) EXPERIMENT TO DETERMINE THE EFFECTS OF pH, CALCIUM, AND ALUMINUM IN LOW CONDUCTIVITY WATER

by

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INTRODUCTION

Recruitment failure has been suggested as a mechanism leading to loss of fish populations in acidified streams and lakes (Beamish and Harvey 1972; Leivestad et al. 1976; Gunn and Keller 1984). Numerous laboratory studies have investigated the effects of pH, aluminum, and calcium, alone or in combination, on early life stages of fish (Brown 1981, 1982, 1983; Brown and Lyman 1981; Baker and Schofield 1982); however, the exposures in these experiments have been of relatively short duration. The objective of the present study was to determine the chronic effects of elevated aluminum concentrations as a function of pH and calcium level on hatching success and subsequent fry survival of brook trout.

METHOD

Brook trout eyed eggs (25 per chamber) were exposed to a replicated matrix of four levels each of pH and calcium and five levels of aluminum totaling 64 different combinations (Table 4) in a 40-day test (March 10 to April 18, 1984). The levels of pH, aluminum, and calcium were chosen to represent the chemistry of sensitive lakes and streams in eastern Canada, the northeastern United States, and Scandinavia. We exposed fish to higher aluminum concentrations at lower pH levels (Table 4), based on the observation that in acidified natural waters, dissolved inorganic aluminum increases as pH decreases (e.g., Schofield 1982). The results presented here are based on nominal pH, aluminum, and calcium levels.

Table 4. Exposure matrix for aluminum, pH and calcium used in the experiment. Each exposure combination was duplicated; all concentrations are nominal.

Aluminum concentrations ($\mu g/l$) at each pH level (units)[a]			
pH 6.5	pH 5.2	pH 4.8	pH 4.4
0	0	0	0
—	4	12	37
—	12	37	111
—	37	111	333
—	111	333	1000

[a] Calcium concentrations for each pH/aluminum combination were 0.5, 1.0, 2.0 and 8.0 mg/l.

Reverse osmosis, deionized water with 1 mg/l sodium added as NaCl was delivered to four head tanks where the pH was continually adjusted with either sulfuric acid or sodium hydroxide to final pH values of 4.4, 4.8, 5.2, and 6.5. This pH-adjusted water was delivered to 13 proportional flow diluters where calcium ($CaCl_2$) and aluminum ($AlCl_3$) were added. Flow to each 600 ml exposure chamber provided 65 volume replacements each day. Chamber temperatures averaged 10.9 C (SD = 0.52) with a photoperiod set at 16-h light and 8-h darkness. Partial correlation and stepwise linear regression analyses were used to determine the linear effects of pH, aluminum, and calcium on fish hatching, survival, and growth.

RESULTS AND DISCUSSION

Egg survival was not significantly correlated to levels of calcium (independent of Al and log H^+), aluminum (independent of Ca and log H^+) or log H^+ (independent of Ca and Al) ($p > 0.01$). Hatching success and survival were negatively correlated to log H^+ and to aluminum concentration ($p < 0.001$). However, hatching success was not significantly correlated to calcium concentration (Figs. 10 and 11). The effects of aluminum on hatching success and survival were most pronounced at lower pH levels (pH 4.4 and 4.8). Furthermore, a protective effect of low aluminum concentrations on survival was observed at each pH level (Fig. 12). While growth was positively correlated to calcium and negatively correlated to log H^+ ($p < 0.001$), no significant correlation was evident with aluminum concentration (Fig. 11); moreover, these effects on growth were most evident at elevated levels of calcium (2.0 and 8.0 mg/l) and pH (5.2 and 6.5).

As aluminum and acidity increased, the frequency at which embryos failed to escape from the chorion during hatching also increased, usually resulting in the death of the embryo. Apparently the effects of aluminum and low pH become evident during the hatching process and continue through yolk absorption, while the protective effects of calcium are not noted until after hatching.

This research was supported by the Electric Power Research Institute under contract RP-2346 with the University of Wyoming.

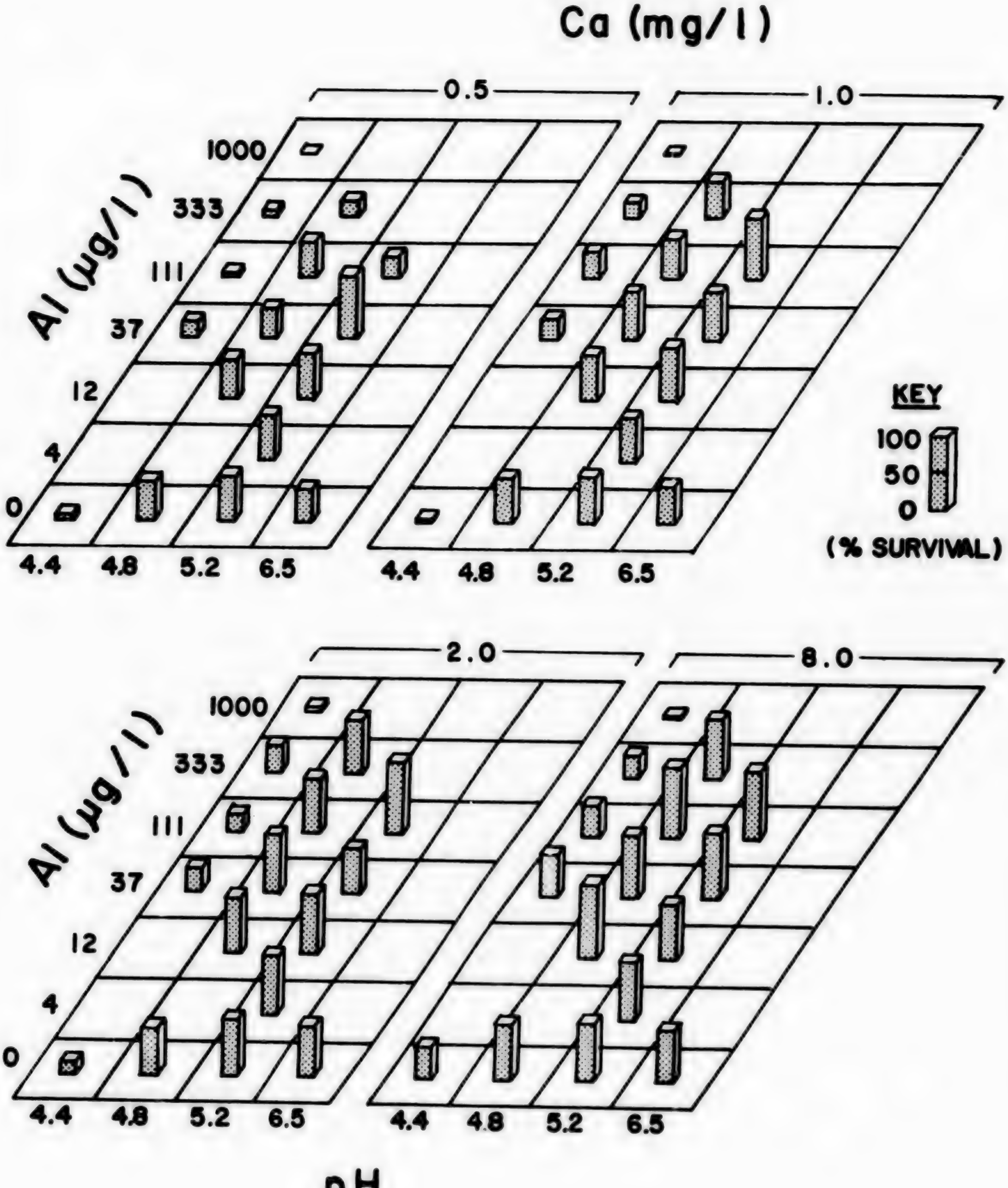


Figure 10. The effect of pH, aluminum, and calcium on brook trout survival through day 40.

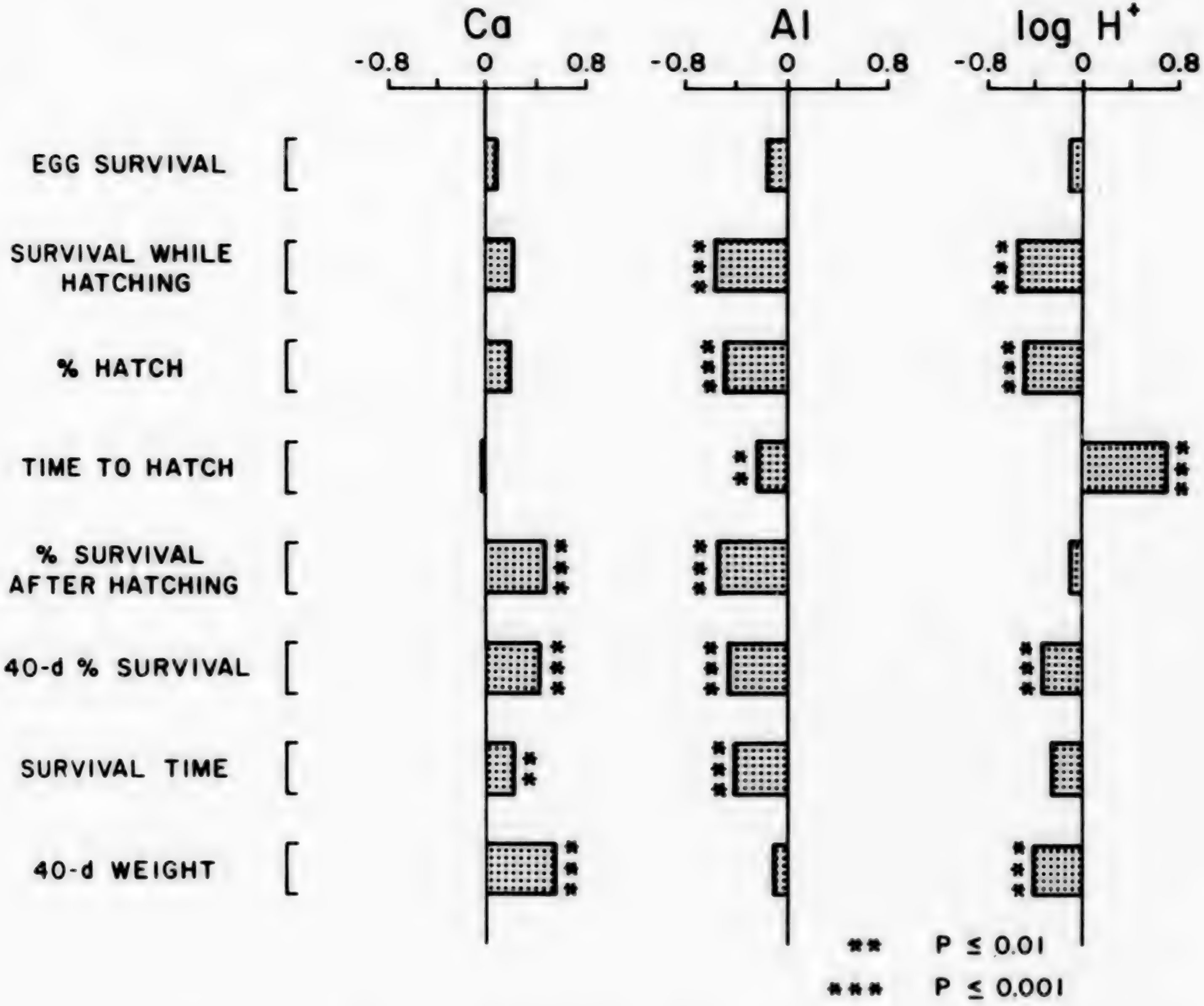
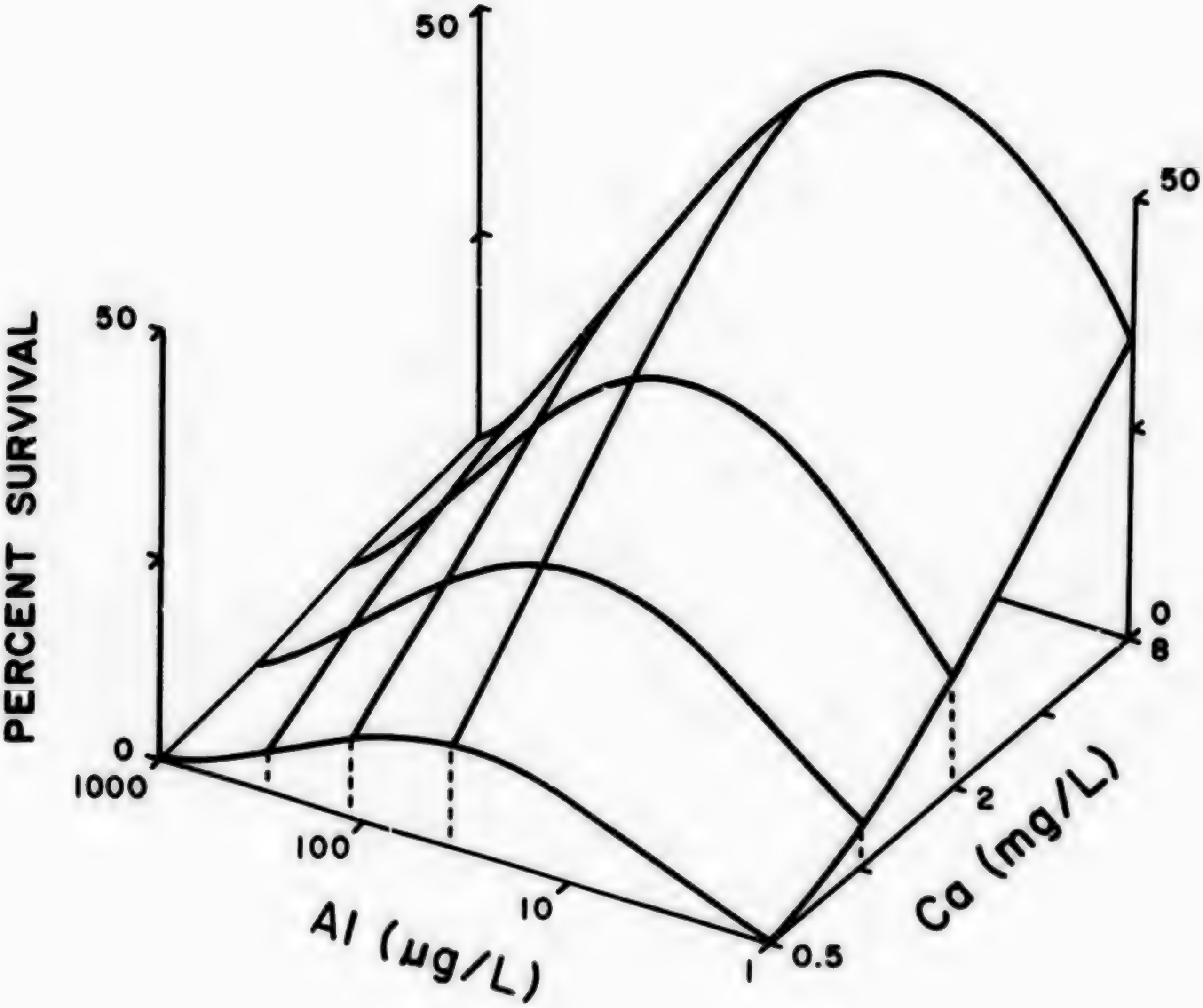


Figure 11. Partial correlation coefficients of the response of brook trout to calcium, aluminum or log H^+.



BROOK TROUT SURVIVAL TO DAY 40:
EFFECTS OF Al AND Ca AT pH 4.4

Figure 12. Stepwise linear regression of the effect of aluminum and calcium on brook trout survival through day 40 at pH 4.4. Dashed lines indicate nominal exposure concentration.

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THE CASE FOR EFFECTS OF ACID DEPOSITION ON ONTARIO FISHERIES

by

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ACKNOWLEDGMENTS

The authors are indebted to F. Hicks, W. Keller, T. Stewart, K. Suns, and D. Wales for the provision of unpublished data. We would like to thank P. Evans, H. Ohashi and C. Malinsky for their assistance in report preparation, and D. Brakke, T. Brydges, J. Eilers, N. Hutchinson, M. McMurtry, J. Munro, W. Scheider, and D. Wales for manuscript review. This research is part of the Ontario Ministry of Natural Resources Fisheries Research Program and the Canada Department of Fisheries and Oceans Acid Rain Program.

INTRODUCTION

Some of the earliest evidence of acidification of North American surface waters (Gorham and Gordon 1963) and the resulting loss of fish populations (Beamish and Harvey 1972) comes from the province of Ontario. We review the current status of information on the effects of acidic deposition on Ontario's fisheries resources and highlight preliminary results from two research programs designed to supplement existing knowledge.

THE CURRENT EVIDENCE FOR IMPACT IN ONTARIO

EVIDENCE FROM LAKES NEAR POINT SOURCES

In Ontario, both fish habitat and fish communities have been lost near point source emissions such as Sudbury and Wawa. One of the most complete examples of fish community loss that have been reported by Harvey and his students for lakes near Sudbury, Ontario is the chronology of species losses coincident with the acidification of Lumsden Lake (Beamish and Harvey 1972). Harvey and Lee (1982) summarized the results of this and other studies, in the La Cloche Mountain area near Sudbury, reporting that 54 fish populations have been lost due to the combined effects of long-range transport and a large point source of sulfur dioxide. Known losses of lake trout (*Salvelinus namaycush*) and brook trout (*Salvelinus fontinalis*) populations from lakes in the vicinity of a second Ontario point source, Wawa, were documented by Somers and Harvey (1984). They estimate that 83 fish populations have been lost from the lakes and concluded the losses were primarily the result of acidic deposition from Wawa smelting operations.

Results from the experimental acidification of Lake 223 in northwestern Ontario (Mills 1984) confirm field observations of population loss and shifts in community structure. During the progressive acidification of the lake, Mills observed that fathead minnows (*Pimephales promelas*) disappeared at pH 5.6 and were replaced in dominance by pearl dace (*Semotilus margarita*). Recruitment failure in lake trout and white suckers (*Catostomus commersoni*) occurred as acidification was continued, at pH 5.4 and 5.1, respectively.

Our ability to generalize from observations in lakes near point sources to other areas of the province is constrained by the potential synergistic effects of high metal levels and low pH in many of these lakes, and by uncertainties about how the historic levels of deposition that caused these losses relate to current levels of deposition in areas distant from point sources.

Recent improvements in water chemistry coincident with the reduction of emissions from Sudbury area smelters (Keller and Pitblado 1985) and the resumption of recruitment by some fishes suggest that habitat losses can be reversed if emissions are reduced. For example, surveys of Whitepine Lake in 1978 and 1980 indicated that a once thriving lake trout population had been reduced in abundance and was no longer recruiting. Only a few large adults (55.8 - 62 cm) were captured with intensive netting. Local anecdotal information suggested the fishery had declined in the 1960's and 1970's. In

Elevated tissue concentrations of mercury, lead and cadmium have been measured in several species of fish in lakes remote from point sources of pollution. The concentration of these metals in fish is inversely correlated with lake pH (Suns 1983; Wren and MacCrimmon 1983) and/or alkalinity (Scheider et al. 1979). Fraser and Harvey (1982) compared the elemental composition of bone of white suckers from 3 acid lakes and 3 reference lakes with circumneutral pH. They found that the bone was decalcified in fish from the 3 acid lakes and speculated that low bone mineral content could cause skeletal deformities, increase susceptibility to other stresses and interfere with ova formation.

Our lack of direct evidence of effects of acidic deposition on fisheries in lakes remote from point sources is likely related to a combination of 4 factors: a period of observation that is short relative to actual rates of change; the large degree of natural variation of fish communities; the intensity of effort required to document mortality of wild fish coincident with episodic acidification; and, our relatively small sample of intensively studied communities. Alternatively, in Ontario, surface water acidification may not be currently affecting fish communities in waters distant from point sources.

RESEARCH PROGRAMS IN ONTARIO

Two research programs currently underway in Ontario will assist in filling gaps in our knowledge. The first is a coordinated program of the Ontario Ministries of Natural Resources and the Environment, part of the Acid Precipitation in Ontario Study (APIOS), and the second is a program of the Canadian Department of Fisheries and Oceans, part of the Long Range Transport of Airborne Pollutants Project (LRTAP).

The objectives of these two programs are similar:

(1) to provide both documentation of current damages and predictions of future damages to fish communities as support for the negotiations on emissions control and for input into fisheries management decisions. Studies conducted to address this objective are described below.

(2) to develop and evaluate techniques for the interim protection and rehabilitation of fish communities that are stressed by acid deposition. We are addressing this objective through experimental studies of liming of lakes and stocking of hatchery fish.

The studies to document losses and estimate future losses can be grouped into four areas: surveys, toxicity studies, case histories and modelling.

SURVEYS

A description of the current chemical and biological state of lakes in Ontario is essential to both estimates of damages to date and predictions about future losses. Water chemistry data have been collected for 4,505 lakes, while information on lake morphometry and the presence of fish species exists for 8,862 lakes.

A computerized Comprehensive Data File has been prepared for the approximately 2,933 lakes for which we have both chemical and fish community data. Analyses of these data have shown that thousands of sensitive lakes exist in Ontario. For example, in a survey of 605 brook trout lakes, we found that while less than 1 percent had pH levels less than 5.0, 3 percent of the lakes were acidic (alkalinity ≤ 0 uEq 1^{-1}) and 26 percent had alkalinities between 0 and 40 uEq 1^{-1}, (Fig. 14) a level below which lakes are considered extremely sensitive to continued high deposition (OMOE 1981).

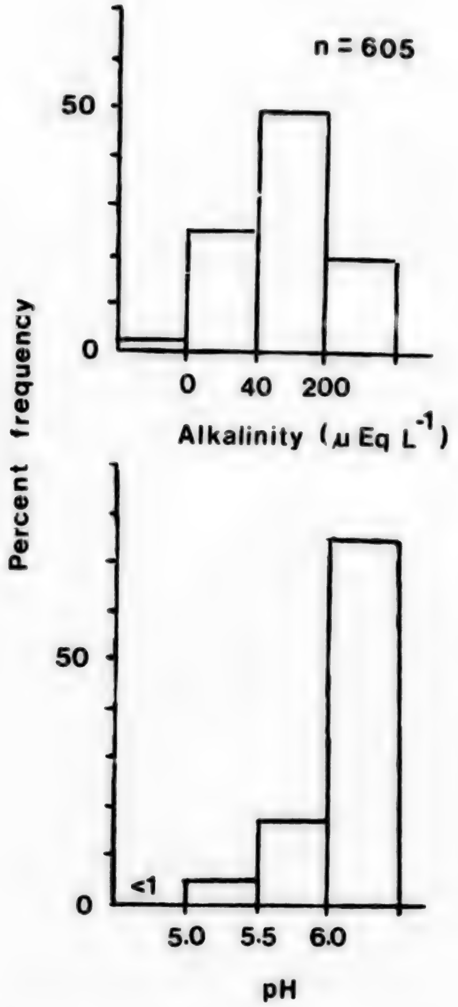

Figure 14. Inflection point alkalinity and pH of 605 Ontario brook trout lakes.

TOXICITY STUDIES

A central assumption in our models of fisheries response to surface water acidification is that the rate and extent of fish losses can be predicted from an understanding of the direct toxic effects of pH and aluminum on the survival of the early life history stages of fish. Three approaches are being used to test this hypothesis:

(a) Laboratory bioassays: The early life history stages of lake trout, brook trout, smallmouth bass (Micropterus dolomieui), lake whitefish (Coregonus clupeaformis) and other species are being tested in a matrix of pH and aluminum levels in soft water in both short-term and chronic exposures.

(b) In situ bioassays: These same species have been exposed in a variety of test containers to a range of natural levels of pH and aluminum in streams, along lakeshores and on spawning shoals.

(c) Comparative surveys: Surveys have been conducted on lakes that either still contain or were known to have contained lake trout, brook trout, smallmouth bass and walleye (Stizostedion vitreum vitreum). Lakes were selected to represent a range of water chemistry that would include the suspected lethal concentration of hydrogen ion for that species.

Some results from our comparative surveys of 24 lake trout lakes are shown in Figure 15.

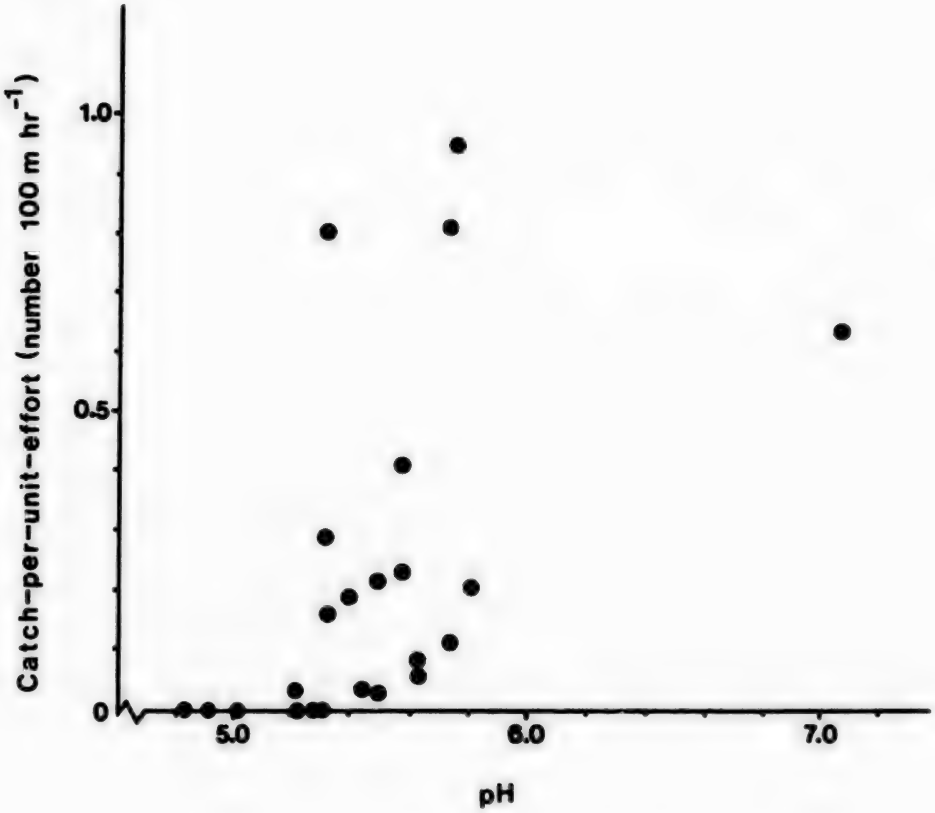

Figure 15. The relationship between catch-per-unit-effort (number 100 meter-hours^{-1}) of native lake trout and mid-lake, summer epilimnetic pH in 24 Ontario lake trout lakes.

Catch per unit effort (CUE expressed as number per 100 meter-hr) of native lake trout declines in lakes with pH levels less than or equal to 5.3. We were unable to catch lake trout in lakes of pH less than 5.2. Analysis of age frequency distributions of lake trout populations and the results of in situ bioassays suggest that the mechanism for population loss is recruitment failure due to the direct toxic effects of pH and aluminum on eggs and newly hatched fry (Beggs et al. 1985).

We view the use of laboratory bioassay, in situ bioassay and comparative surveys as essential to understanding fish toxicity - the inter-comparison of results provides a powerful analytical tool to test the early life history hypothesis and to develop predictive models.

CASE HISTORY

Time series of chemical and fisheries data are being collected from low alkalinity lakes in both the Dorset and Algonquin areas of Ontario.

Lakes have been chosen because of their small size and low alkalinity. The case histories are designed to test our predictive models and to document the response of fish communities to surface water acidification. As these lakes acidify, we are attempting to link changes in fish communities to changes in water chemistry or to other stresses. For example, we are investigating recruitment failure in a population of white suckers in Westward Lake (pH 6.25) (Fig. 16).

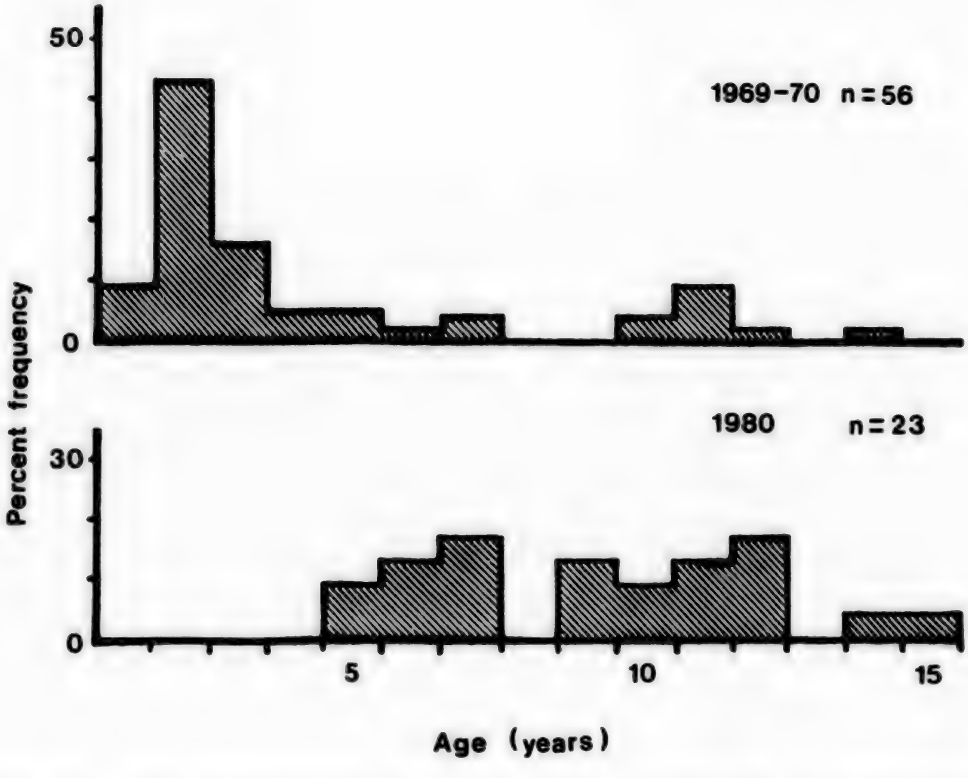

Figure 16. Age composition of white suckers captured in Westward Lake (Algonquin Park) in 1969-70 and 1982.

The white sucker population is currently composed of a small number of fish of 5 years or older. In the late 1960's and early 1970's, suckers were more abundant and although older age classes were sporadic, the population was recruiting. In a comparison of age frequencies of white sucker populations from thirty low alkalinity Ontario lakes, no other populations with symptoms of successive recruitment failure were found. Preliminary results of experimental work indicate that white sucker eggs from another self-sustaining population, incubated at Westward Lake, will hatch. Mortality of Westward suckers may occur after the young emerge or the adult suckers may not produce viable eggs. Alternatively, the reproductive failure of white suckers in Westward Lake may be unrelated to acidification.

MODELLING

Our approach to assessing damages and risks to Ontario fisheries resources from acidic deposition has involved the development of a variety of models that both bound the real value of resource losses in the province and allow us to design effective research programs to address uncertainties in our knowledge. Three models have been developed:

(a) Large scale risk assessment models: Jones et al. (1984) used a simple model developed in workshops and data from surveys to predict the rate andextent of future fisheries resource losses in Eastern Canada. The authors used survey information on the distribution of lake characteristics presumed to influence sensitivity to acidification to scale a site model to whole regions. The site model is comprised of equations to predict the steady state concentrations of calcium, magnesium, alkalinity and sulfate. This is combined with assumptions on deposition rate to produce predictions of rates of change and eventual future state. For some Ontario areas, the model predicts far greater effects than have been observed to date. Current efforts are directed at testing hypotheses to account for the discrepancy between predicted and observed.

The other two models are statistical models that estimate losses to date:

(b) Preliminary risk model: Minns (unpublished data) used the fisheries and chemistry survey data to estimate the number of acidified lakes in Ontario and the sensitivity of fisheries resources to continuing deposition. The results suggest that 2,000 Ontario lakes are acidified and some 18,000 lakes, including a significant number of lake trout, brook trout, and some smallmouth bass lakes, are extremely sensitive to future acidification.

(c) Lake trout damages model: Beggs et al. (1985) used information on the distribution of lake trout across the province and the water chemistry survey data to estimate the proportion of lake trout populations in Ontario that had been lost because of acidification. They developed a discriminant function which distinguished between extinct and extant lake trout populations in 173 lakes. The function was clearly related to acidification. Inorganic aluminum (estimated from pH, total aluminum, and dissolved organic carbon) was the most important variable in the function. As most lake trout lakes have not been sampled for these variables, a second function, incorporating only pH was developed. This function was then applied to all lake trout lakes sampled and the result extrapolated to estimate that 3 percent of lake trout populations in Ontario have been lost due to acidification. When the Sudbury area was removed from consideration due to the large influence of point sources, it was estimated that lake trout are extinct in less than 1 percent of lakes in other areas of Ontario. The authors also estimated that 12 percent of lake trout lakes outside the Sudbury area are currently acidified or extremely sensitive (alkalinity <40 uEq L^{-1}) to acidic deposition.

CONCLUSIONS

We have evidence of both habitat and fish community loss in areas of Ontario adjacent to point sources. In areas distant from point sources, we have observed toxic chemical conditions during snowmelt, symptoms of stress in several fish populations in lakes of low alkalinity, elevated levels of metals in fish, and mortality of native fish coincident with snowmelt. Although we have no evidence of current widespread loss of fish populations or communities, we believe that a significant proportion of the fisheries resource in Ontario is susceptible to change with continuing deposition of acid.

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MECHANISMS AND CAUSES OF FISHERY DECLINE

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SUMMARY

Present evidence of the decline and loss of fisheries from acid waters suggests that water quality, particularly calcium, aluminum, and acidity, is crucial to their maintenance. It is not clear, however, whether sustained or episodic conditions are more important, nor to what degree water quality is determined by atmospheric deposition alone. It follows that the benefit to be expected from reduced emissions is quite uncertain, and while some decrease in sulfate or acid deposition might result, this is likely to be insufficient to improve the fisheries of the sensitive affected lakes, as well as ineffective as a short term measure. Manipulative treatments to catchment soils or surface waters offer a more certain outcome and techniques of soil treatment or stream quality control need to be developed.

INTRODUCTION

The reported decline and loss of fish from acid waters has been widely attributed to the acidification of surface waters. While acidity is a common factor, surprisingly, fish are sometimes present in acid environments, and, of course, sometimes absent from scarcely acid, or even circumneutral waters. Determinants of a fishery are varied and complex - they include hydrological characteristics, lake/stream morphometry, habitat complexity, incidence of disease, temperature regime, water quality, food supply, and toxic pollution. Characteristically, acid waters are found in upland areas where first order streams or small lakes lie on fast draining slopes with thin, poor soils, and where afforestation exacerbates natural fluctuations, or where drainage is influenced by bogs or peaty soils. While poor water quality (and specifically acidity) is an important limitation to fish survival in these waters, associated conditions are often inhospitable (e.g., Hynes, 1970).

The argument that progressive acidification has led to fishery decline implies that water quality has become progressively poorer, either due to additional atmospheric impact or to changed catchment conditions. Unfortunately, there are few good data available on historic water quality conditions. Laboratory exposures to fish, mostly short term, do not always satisfactorily explain field observations.

This review will consider published data on fishery status and water quality for several affected locations, seeking a relationship to three important water quality components - acidity, calcium and aluminum - that appear most pertinent to fishery status in acidified waters.

EVIDENCE FOR CHANGED FISHERY STATUS AND WATER QUALITY

Examples of changed fishery status and present water quality characteristics are given in Table 7, together with otherwise similar, circumneutral, lakes which retain their fisheries. It is evident that few generalizations can be made for such a diverse set of data, involving

Table 7. Comparison of water quality with observed fishery status

(Assumptions are that pH-Ca-Al determines fishery status, and that mean data for lake sets are representative of individual lakes)

Lake set (n)	Concentrations (μeq l^{-1})					Fishless Observed (%)	Fish or Community
	pH	Ca^{2+}	SO_4^{2-}	Al^{3+}	Ca/H		
Adirondacks (217)	4.95	102	134 (by difference)	22.8	8.5	51	mixed species
S. Norway (616)	4.75	36	71	18.1	2	37	brown trout
Sudbury, Ont. (208)	6.2	272	250	(5.5)	68	28	mixed species
Galloway, Scotland (57)	4.95	74	111	14	6.2	5	salmonids
C Sweden (32)	5.35	271	242	8	60	22	char
N & C Sweden (101)	7.0	355	210	-	335	0(?)	mixed species
N Norway (47)	5.1	52	59	5	6.2	0	salmonids
Whitefish I.R. Ontario (35)	6.5	282	368	-	282	0(?)	mixed species
ELA, N.W. Ont. (102)	6.5	95	76	-	95	0(?)	mixed species

Source: Howells 1984

different fish communities. Valid relationships between fisheries and water quality are hard to identify.

S. NORWAY LAKES

This is one of the few extensive data sets (Wright and Snekvik, 1979) with information for several hundred lakes giving recent water quality and fishery status. In addition some thousands of lakes have been assessed for fishery changes (Muniz et al., 1984) in the same region. The historic changes in the fisheries were derived from questionnaires circulated to local fisheries boards, by interviews, and by test fishing of 88 lakes (Rosseland et al., 1980) (not reported in detail). Wright and Snekvik (1979) found by stepwise multiple regression that log [Ca^{2+}] and pH (in that order) were the two most important chemical variables determining fishery status. All of the lakes with pH approx. < 4.5 and [Ca^{2+}] < 0.25 mg l^{-1} (approx. 12 ueq l^{-1}) were fishless, but only 1/5 of equally acid lakes with [Ca^{2+}] of 2 mg l^{-1} (100 ueq l^{-1}). Similarly, most (70%) lakes with pH > 5.4 but with [Ca^{2+}] < 0.25 mg l^{-1} are fishless, whereas at this pH and with [Ca^{2+}] of >2 mg l^{-1}, all lakes contain fish. Plotting the lakes, as in Fig. 17, in relation to their acidity and calcium demonstrates that fishless lakes are those of low calcium concentration but within a wide range of acidity.

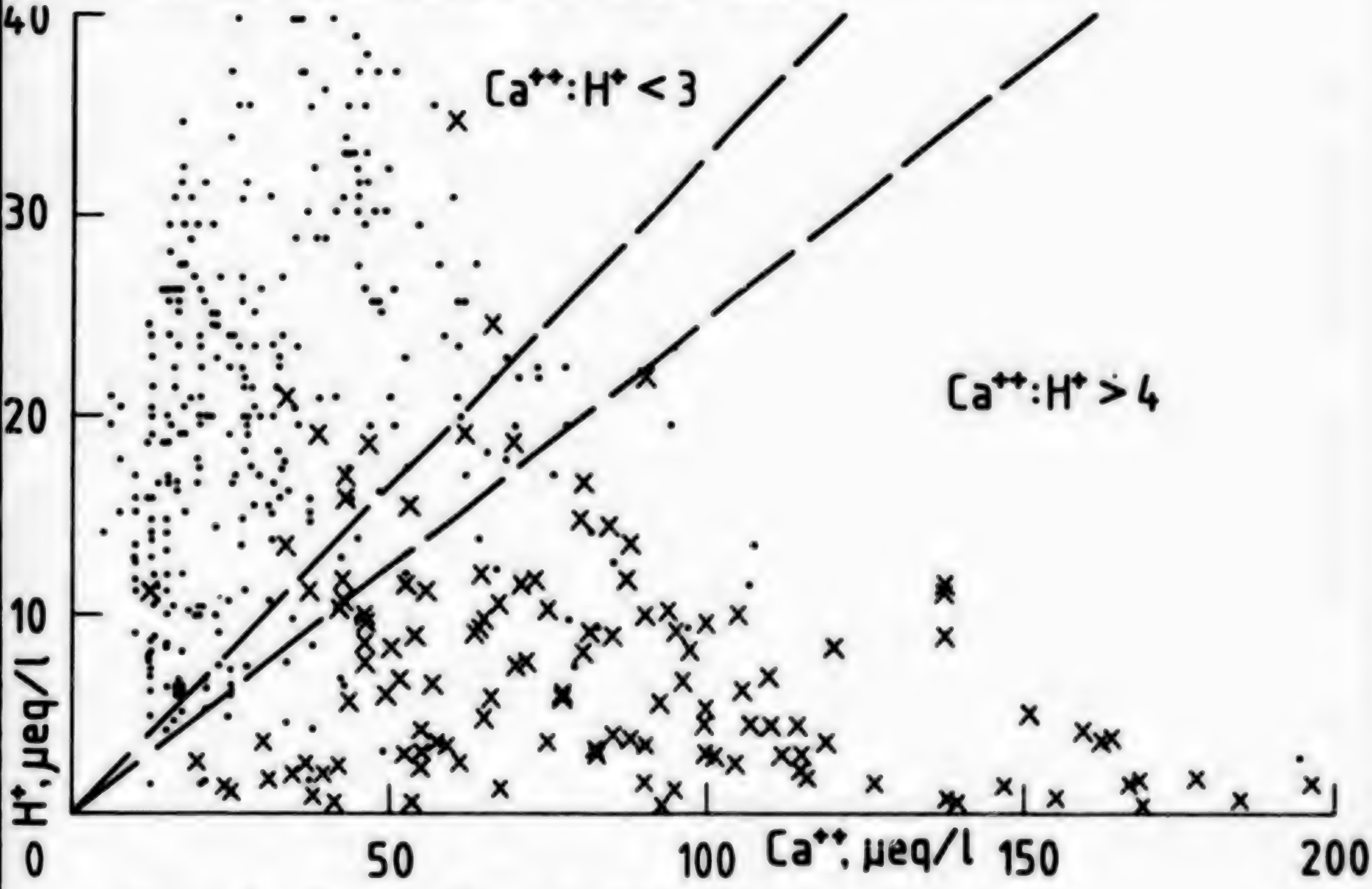

Figure 17. Chemical balance in fishless lakes (.) and in good or overpopulated lakes (x) in Sorlandet

Predominantly the fishless lakes are those with a ratio of calcium:hydrogen of 3 or less. No relationship of fishery status and total aluminum was found (Wright and Snekvik, 1979), possibly because the single water sample was unrepresentative, or because an unknown fraction of the aluminum was available and toxic. However, while aluminum is most toxic within the pH range 5.2 to 5.4, fishless lakes of this acidity have a wide range of total aluminum (approx. 50-150 ug l^{-1}), and some of those that retain fish have high concentrations (Fig. 18), inconsistent with the hypothesis that aluminum is the limiting determinant.

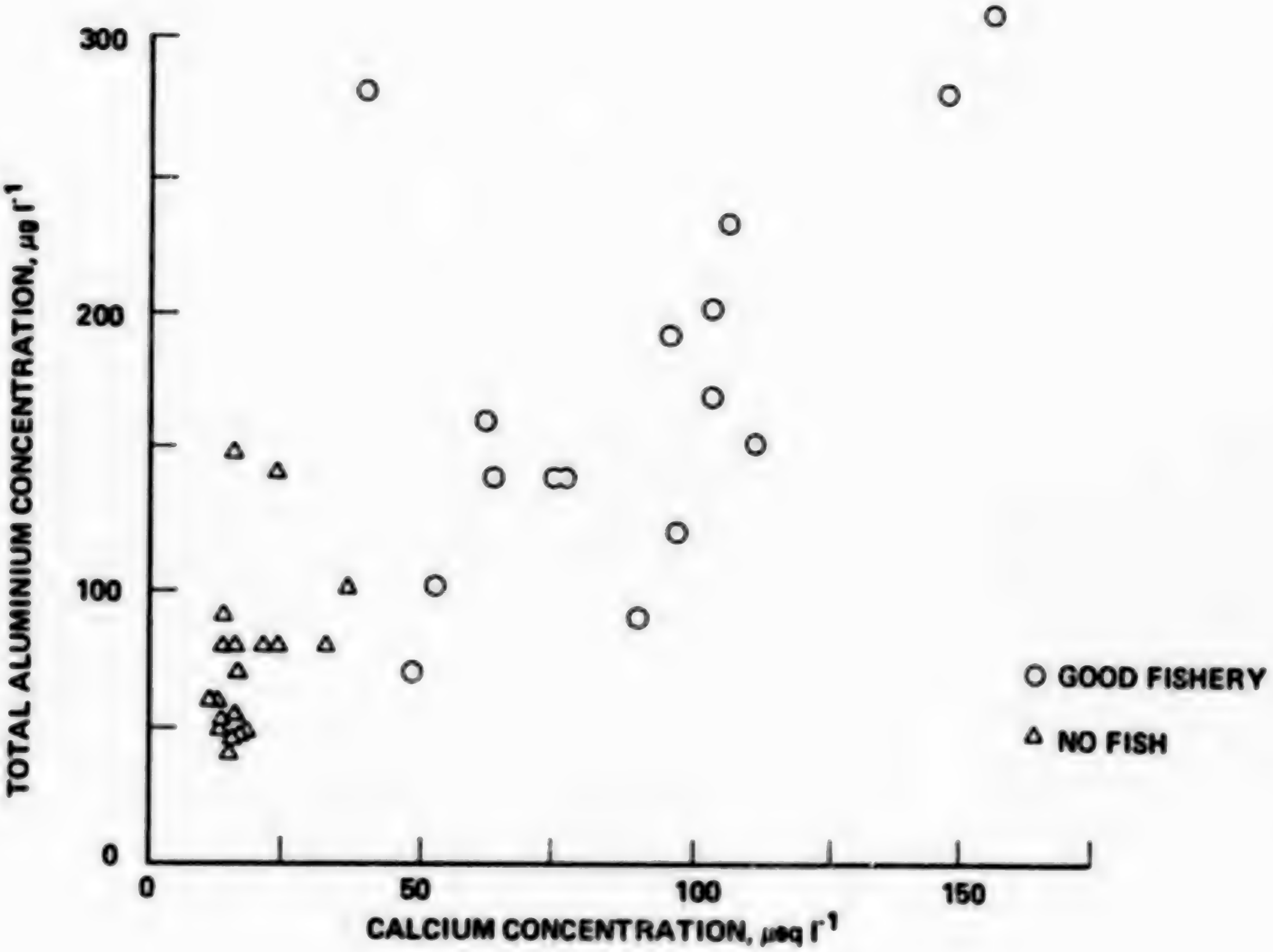

Figure 18. Fishery status of South Norway lakes of pH 5.2 - 5.4

Evidence for a change in fisheries on a regional scale brought about by increased and intolerable exploitation, or of disastrous disease, or other biological reasons, is lacking. It follows that if fishery status is determined by water quality, the latter must have changed over the period of observed fishery changes, principally in calcium content, since it can also be demonstrated that the major variable of water quality associated with acid deposition, sulfate, is not *per se* toxic to fish at the levels observed, nor does the status of fisheries in this data set relate to [SO_4^{2-}]. Indeed, the "worst" lakes are those of lowest sulfate concentration (Chester, 1984), and there is no reason to believe that a change in sulfate of these waters would bring the cation balance (Ca:H) nearer to that tolerable by fish.

The possible reasons for this implied change in water quality include progressive depletion of calcium from soils and underlying bedrock over geological time, the sequestration of available calcium by an increased biomass within the lake catchments, the progressive loss of calcium yielding material (soils) by erosion, or a change in opportunity for neutralizing drainage waters by altered hydrological regimes (Krug and Frink, 1983). Evidence for changes of this kind in the region of S Norway is not generally available, although major changes in land use have been dismissed (Drablos et al., 1980).

CENTRAL AND WEST SWEDEN

There are two pertinent data sets of Swedish lakes fishery data, with accompanying data on water chemistry.

The report by Dickson et al (1975) refers specifically to 36 char (Salvelinus alpinus) lakes in central Sweden for which there are past and present records of fish species present, and of recent water chemistry. The number of species has the expected relationship with pH (Fig. 19) with char lost from 11 lakes, in 4 from causes other than acidity.

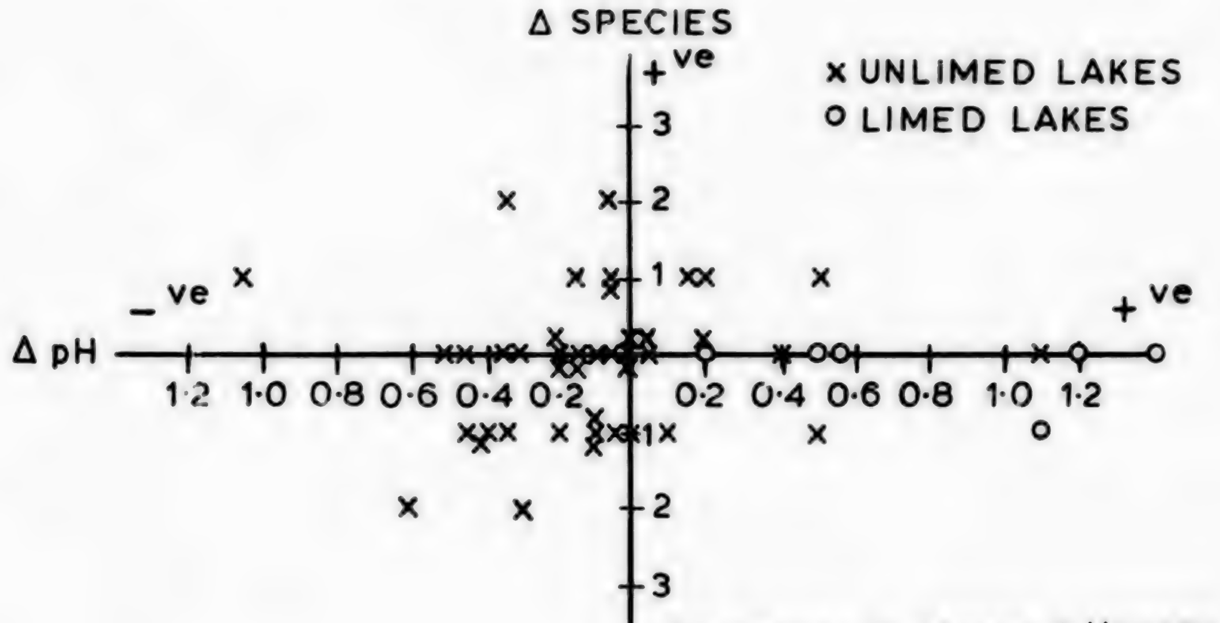

Figure 19. Changes in 55 Swedish lakes 1971-76

In 7 lakes (pH 5.7 - 4.5), calcium is 1.6 to 4.6 mg l^{-1} (80-230 ueq l^{-1}) and aluminum 110 to 275 ug l^{-1} (10-25 ueq l^{-1}). Unlike the fishless brown trout lakes of southern Norway there is no consistent pattern associated with the ratio of calcium:hydrogen or of calcium:aluminum concentrations. Experimental study of this species does not explain the loss of fish from lakes of such diverse chemistry.

The reports of changes in west coast lakes (Almer et al., 1974; Almer et al., 1978) derives from a set of 383 lakes of which 50 have records of past and present fishery status, and of changed acidity. In 1970, roach (Rutilus rutilus) were absent from 10 of the lakes. The same lakes (n = 55) are later reported (Almer and Hanson, 1980) to have changed fishery status and acidity over the period 1971 to 1976 (Fig 20). Two of the lakes had no fish in 1971. Of those that became more acid (24), six lost 1 or 2 species and typically the remaining species became more numerous or catch weight increased. Eight of the more acid lakes increased in species. None of the lakes with lost species showed change in alkalinity, the only other chemical component reported.

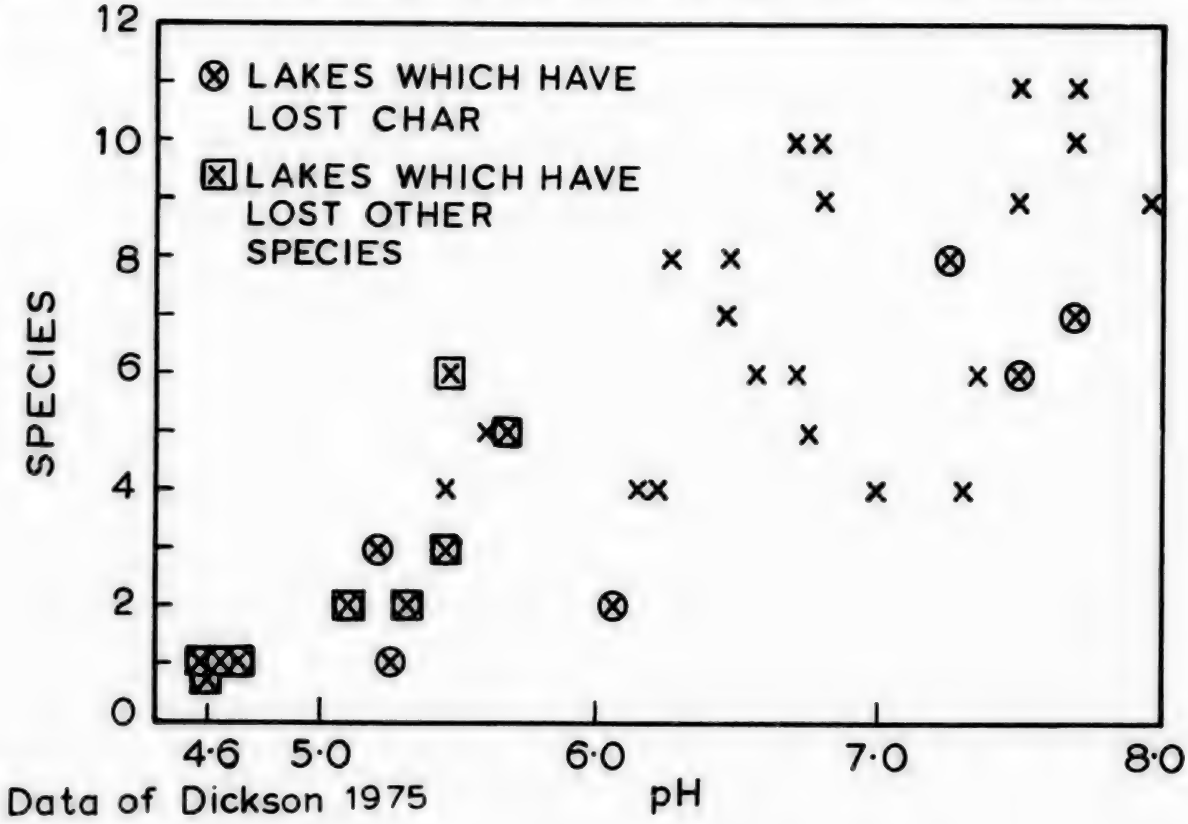

Figure 20. Species diversity in Swedish char lakes

Although other Swedish lakes have lost fish species, it is difficult to trace associated water quality, or even pH records for the individual lakes, which might be helpful in exploring these relationships (IERE, 1981). A further problem is that in these mixed species lakes interactions between species (Magnuson et al., 1984), or complex interactions with a range of environmental variables (Henderson, 1984) may be operating.

ADIRONDACK LAKES

Historic fishery records provide evidence of the loss of fish communities from 21 of 40 high altitude lakes over past decades; 19 of the lakes are of pH < 5. Water quality information for the individual lakes is not reported, although those of pH < 5 have Ca < 2 mg l^{-1} (100 ueq l^{-1}) and Al generally in excess of 300 ug l^{-1} (27 ueq l^{-1}) (Schofield, 1982). A more extensive survey of 849 ponds and lakes (Pfeiffer and Festa, 1980) provided evidence of loss of stocked brook trout in 180 ponds but details of water quality are not given. Adirondack lakes and ponds appear to be inhospitable now for some species which have been maintained over the past century by stocking (Brown and Brocksen, 1982). Changes in the level of stocking over the past few decades are evident, as well as in exploitation pressure, which make interpretation of changes attributable to water quality change difficult (Fig. 21).

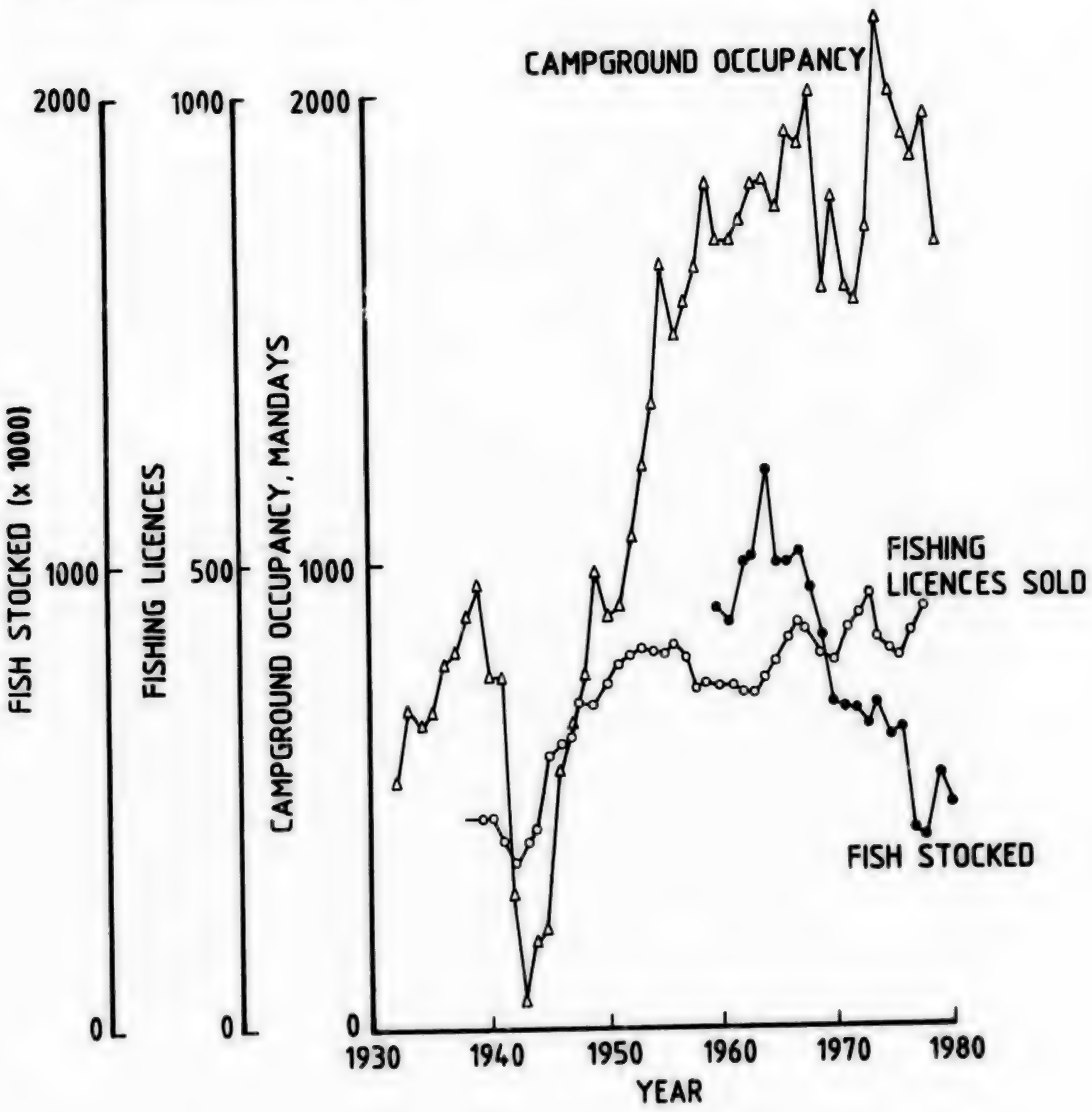

Figure 21. Fish stocked and fishing pressure in Adirondacks, 1940 to 1980

ONTARIO LAKES

Lakes close to the Sudbury smelter have lost fish and information on water quality is available. In all Ontario, 230 lakes are listed as lacking fish (Minns, 1981) but since their average pH is < 6.5 some lakes must lack fish for reasons other than acidity, even though most (73%) are in catchments adjacent to the Sudbury smelter.

In a sampled 75 lakes (Kelso et al., 1982), brook trout (*Salvelinus fontinalis*) and white sucker (*Catastomus commersoni*) were not found in lakes greater than 1.6 ha with pH < 5.8 and < 5.2 respectively. While the 38 fishless lakes were more often those of low pH and alkalinity, some (19) had pH > 5.5 and were presumably tolerable to some species at least. Calcium was >2 mg l^{-1} and aluminum (mean) about 50 ug (4.5 ueq) l^{-1} in these lakes. Chemical data for 209 lakes in the Sudbury region (Wright, 1983) give mean pH of 6.2 (range 4.3 - 8.5) and calcium 5.4 mg l^{-1} (272 ueq l^{-1}). A smaller sample of these lakes suggests that aluminum is about 300 ug l^{-1} and that trace metals may be high (Howells, 1983). Again, no clear relationship emerges between fishery status and pH, calcium and aluminum. Changed fisheries in 19 of 67 lakes in the Sudbury area (Harvey, 1975) are thought to be associated with changes in water quality, since the most acid lakes are closest to the local emission source, assuming that the spatial gradient represents a temporal trend. This would suggest that alkalinity (and calcium and magnesium) had been reduced in parallel with fishery changes.

ACID WATERS IN BRITAIN

Acid waters and the status of their trout fishery have been investigated recently in lakes and streams in Britain. In Galloway, southwest Scotland, 5 of more than 70 lakes have lost, or reduced, their brown trout stocks over the past decades (Harriman and Wells, 1984). In 4 lakes, diatom analysis of sediment cores suggests that recent acidification began about 150 years ago, although the lakes were already acid (pH < 6) prior to the nineteenth century (Battarbee, 1984). Today, Galloway lakes are generally acid (mean pH 4.95), and low in calcium (mean 1.5 mg l^{-1}, 75 ueq l^{-1}) although total aluminum is not particularly high (mean 125 ug l^{-1}, 11 ueq l^{-1}). Headwater streams in Cumbria, the Peak District, and Wales, draining millstone grit, granites or other "hard" geology, include some which lack fish, but they are quite diverse in their acidity, calcium and aluminum concentrations (Prigg, 1983; Stoner et al., 1983; Sadler and Lynam, 1984) (Table 8). For Welsh and Scottish streams, those draining coniferous forests are significantly poorer in water quality, and in their fishery status. Analysis (Fig. 22) of fish biomass and growth in these upland streams (Turnpenny, 1985) suggests, however, that in poor water quality, condition and growth of trout is good, being apparently regulated by population density.

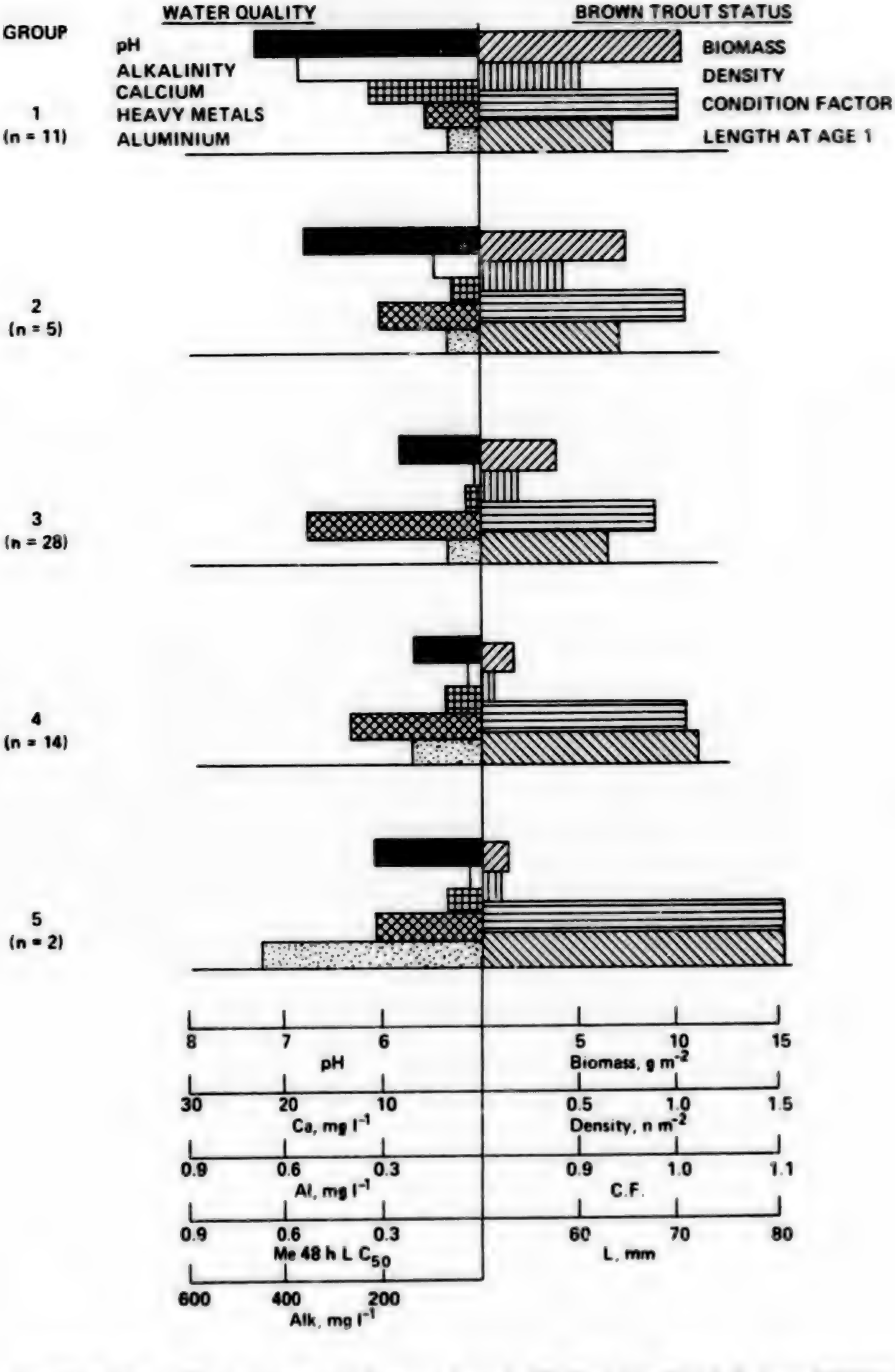

Figure 22. The status of brown trout (Salmo trutta L.) populations (Welsh and Pennine streams).

Table 8. Chemistry of Fishless Stream in the UK

	n	pH	Ca^{2+} ueq l^{-1}	Al^{3+} ueq l^{-1}
Esk and Duddon	10	4.6 - 6.5	55 - 290	23*
Peak	10	4.5 - 7.4	135 - 530	32
North Wales	2	5.2 - 5.5	35	14
Mid Wales	3	5.0 - 5.8	50 - 120	20
SW Wales	8	4.0 - 5.5	300 - 500	31

(* a few measurements during spate conditions)

EXPERIMENTAL STUDIES

Short term laboratory experimental exposures of fish at different life stages have suggested that survival is indeed related to acidity, calcium and aluminum concentrations.

The critical dependence of fish (brown trout, Salmo trutta) survival at low pH on the ambient calcium concentration has been demonstrated (Brown, 1982) (Fig. 23) as well as the sensitivity of the freshly fertilized eggs in low pH, low calcium waters. Comparison of bioassay data for brown trout over a range of pH and calcium concentrations with the field data from southern Norwegian lakes indicates consistency at pH 4.5 and 4.8, but not at pH 5.1, where survival in the laboratory is 100% throughout the range of calcium concentrations tested (0.25 to 8 mg l^{-1}) (Brown, 1983a). This suggests that an additional toxic factor is contributing to the adverse conditions in the field, although aluminum was not implicated in these lakes.

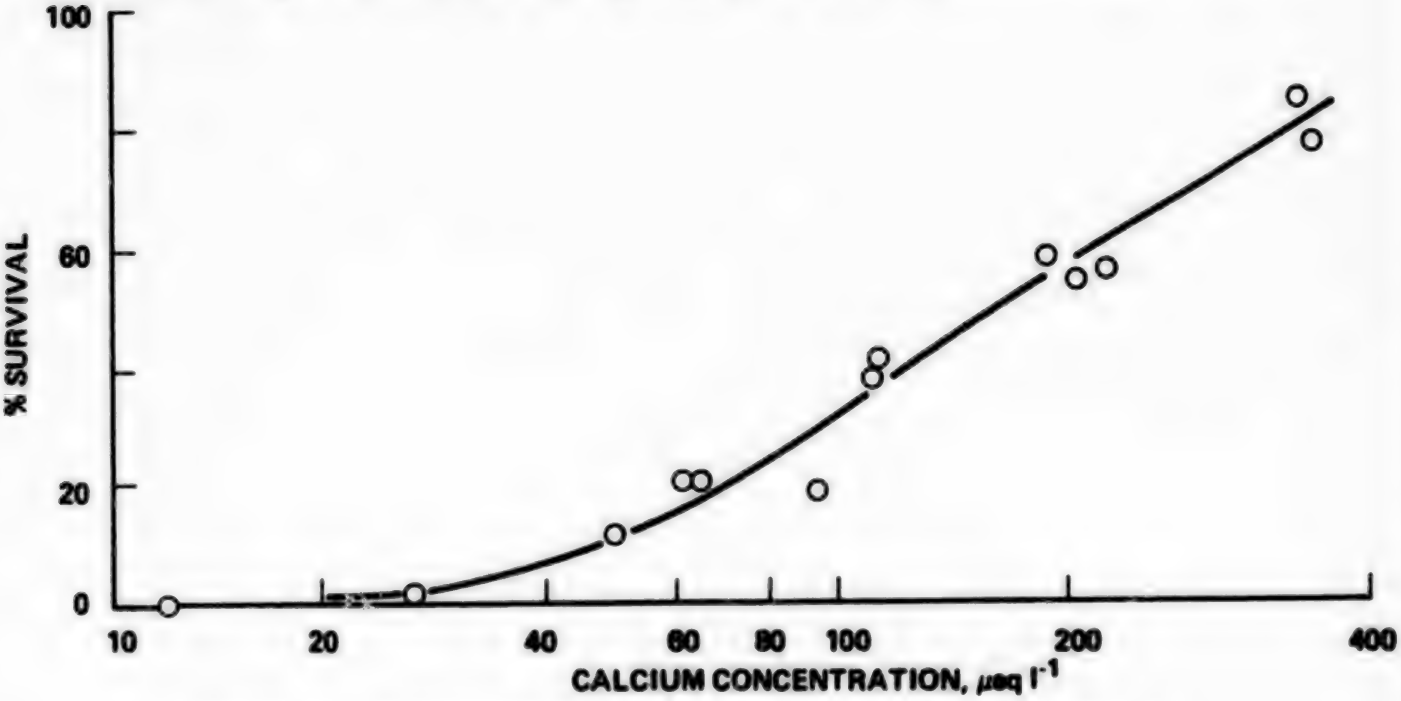

Figure 23. Percentage survival of brown trout eggs at pH 4.5.

Experiments on the survival of yolk sac fry and older stages of brown trout over a range of pH's, aluminum and calcium (Brown, 1983) show its dependence on the concentration of all three, with dosed aluminum toxic at the lowest concentration used (250 ug l^{-1}), a trend towards higher mortalities at the higher test pH's, and a marked difference in mortalities at calcium concentrations of 0.5 mg l^{-1} or less as opposed to 1.0 mg l^{-1} or more. Contrary to the effect of low pH and low calcium concentrations, fish become more sensitive to aluminum as they become older. Experiments using even lower concentrations (to 30 ug l^{-1}, 2.6 ueq l^{-1}) of aluminum indicate that young fry may be affected; possibly the mode of toxicity may be different in fry and older fish (Dalziel and Brown, 1983).

Most laboratory exposures are of relatively short time span; recent work (Sadler and Lyman, 1984) on longer term exposure of brown trout to combinations of acid (pH 4.4, 4.8, 5.2) and low calcium concentrations (0.3 to 2.2 mg l^{-1}), with a constant feeding rate showed no effects of either acidity or calcium on growth over a 6-week period. When starved for a similar period, however, weight losses were 5-10% greater at pH < 4.4.

It is , of course, difficult to transpose the results of bioassay exposures to observations in the field. An approach involving population modelling techniques similar to those used to assess the impact of fishing pressure on exploited populations, and incorporating the bioassay results described, has been used to predict the fishery status of lakes in S. Norway (Sadler, 1983) (Fig. 24).

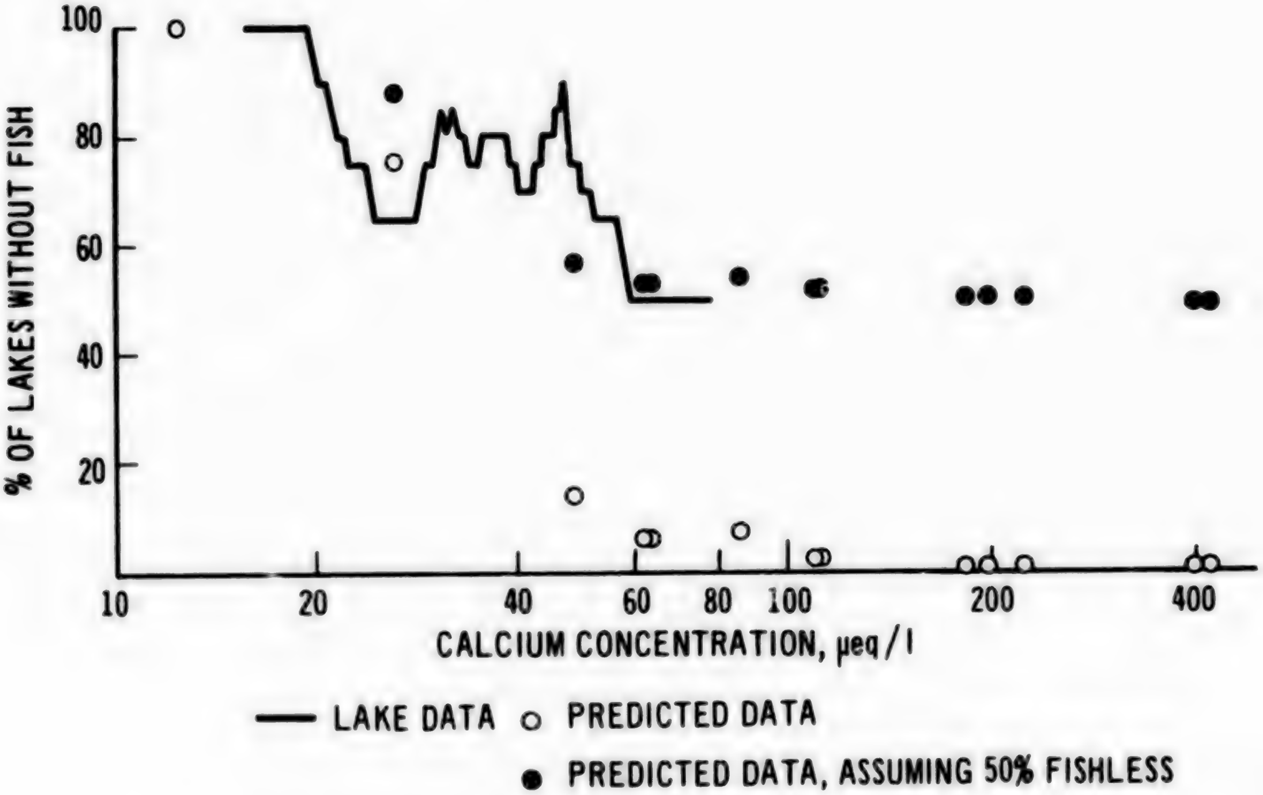

Figure 24. Predicted and observed fishless lakes, S. Norway

However, while the fishless state of lakes of <1 mg Ca l^{-1} (50 ueq l^{-1}) could be predicted by the model, the status of lakes with higher calcium is about 50% worse than expected. Is it that acid water pulses are the agent of population decline, that the life history statistics for brown trout are unrepresentative, or that other unrecorded factors are at least as important as acidity and calcium? Further work is needed before these questions can be answered; in particular data are needed on the pattern of chemical changes during acid episodes, and studies of fish response to real and simulated episodes.

RESTORING FISHERIES

The efficacy of remedial measures to restore lost fisheries must depend on a clear understanding of the causes and mechanisms of decline. If we accept that water quality changes are indeed the major cause, then the means by which surface waters can be returned to a quality suitable for fish must be determined, their practicality tested, and their relative costs estimated.

REDUCTION OF SULFUR DEPOSITION

Leaving aside the uncertain relationships between sulfur emissions and regional, or more localized, deposition, to what extent would a change in deposition benefit fisheries? A number of attempts have been made, using the chemical and fisheries data of S. Norway lakes, to predict fishery improvements. Brown and Sadler (1981) defined a relationship with the sulfate concentration and acidity of approx. 400 upland lakes in S. Norway, which were the most affected. Assuming that sulfate concentrations directly represent deposition, they deduced that a 50% reduction in sulfate deposition would result in a change of about 0.2 pH unit, and on the basis of the observed relationship between lake pH and fishery status, concluded that only about 5.5% of lakes would be improved.

It is evident, however, that fisheries are not determined by pH alone and that individual lakes respond differently. Later studies, reworking the same data, have developed the original concept in greater detail and complexity. In all cases the analysis has, in the absence of historic time-series records, used geographic distribution data to predict temporal change.

Muniz et al. (1984), using a larger group (1034) of the lakes with a wider range of conductivity and with some reassessment of their fishery status, predicted that 51 (9.7%) low conductivity lakes and 70 (13.7%) higher conductivity lakes would recover (11.7% of the total). Similarly 91 (8.8%) poor fishery lakes were expected to improve from "sparse" to "good" status (Fig.25).

Chester (1982) acknowledged the diversity of lake and catchment conditions and categorized five classes (including "bicarbonate lakes") in terms of their "effective catchment reactivity" or the degree to which acidity had been neutralized. This "sub-set" analysis did not indicate that "barrenness" was dependent on lake acidity, or on sulfate or aluminum (total) concentrations. In the absence of a clear relation between fisheries and acidity even a substantial change in lake acidity or in acid input would not be expected to lead to a material improvement. One complicating factor could be the compensating effect of calcium mobilized by acidity within the catchment.

Wright and Henriksen (1983) attempted to take account of a possible change in aluminum and base concentrations in the lakes, assuming a standard value (F = 0.2) to represent the relative change of neutralizing bases (from catchments) and deposited sulfate (strong acid). Predicted values of strong acid (SA) were then used to derive fishery status. Using data for 683 lakes for which recent chemical composition is known, they predicted that a 50% reduction in deposition would restore the water quality of 35% of the lakes experiencing fisheries problems.

While this approach acknowledged the chemical neutralizing effect of calcium and magnesium derived from the lake catchments, and buffering by dissolved aluminum, it ignored the demonstrated benefit of calcium on fish tolerance to acidity and aluminum. This is of particular importance because SA and Ca are negatively correlated (r = -0.37). Thus if the present day SA/fishery status is used to predict fishery changes then reduced SA infers increased Ca concentration whereas the concentration would more likely decrease as a result of reduced acid deposition.

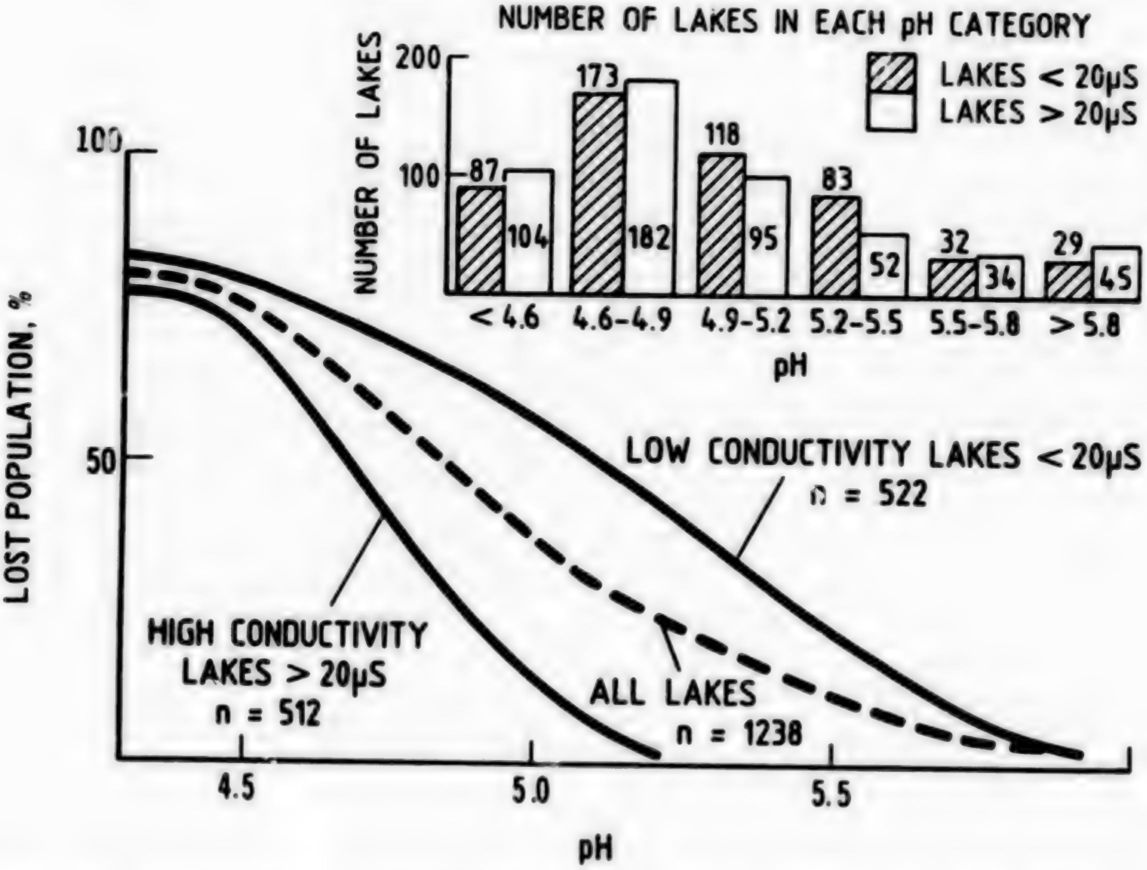

Figure 25. Relationship between the percentage of lakes with lost trout population and pH for lakes in four counties in southernmost Norway. (Data from Sevaldrud and Muniz, 1980).

Sadler and Brown (1984) have sought to overcome this by using the range of "F values" from zero to 0.6 observed for the same data set, instead of the constant F = 0.2 used by Wright and Henriksen derived from predicted changes in strong acid. Mean values of F ranged from 0 for lakes with negative alkalinity (or low Ca) to >0.6 for acid lakes of high Ca (Henriksen (1979) found F = 0.44 + 0.2 for lakes with pH <5). Changes in calcium and SA for each lake were calculated and the expected fishery status (based on the lake survey) derived for this water quality. The improvement expected from acid deposition is smaller than that estimated by Wright and Henriksen with a 50% reduction resulting in only 5.5% of the lakes with present fishery problems being restored. Even complete reduction was predicted to have only limited benefit (Fig. 26), a deduction not inconsistent with historical records, since southern Norwegian lakes are long known to have suffered from fishery problems. Dahl (1921) reported loss of fish populations in this area in the 1920's and noted that problems had also been found a generation earlier when S deposition must have been lower than today. Hatchery waters were also treated with lime in the 1920's to increase pH and calcium levels to improve survival (Dahl, 1926; Bua and Snekvik, 1972).

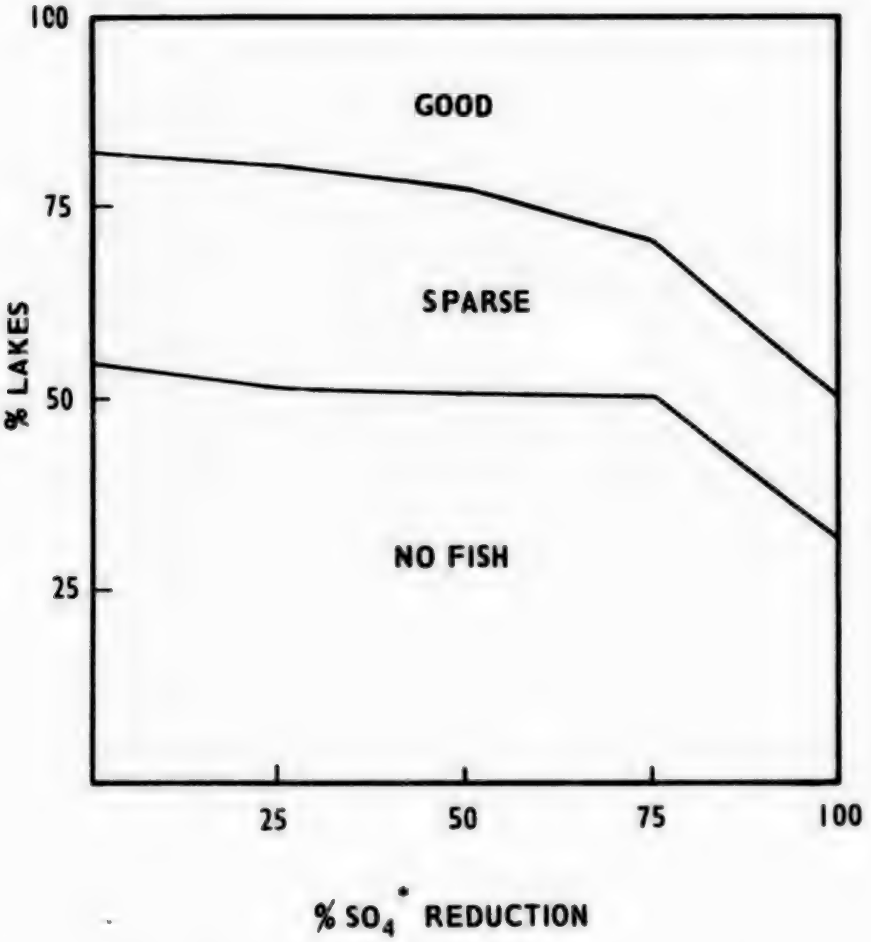

Figure 26. Fishery status of lakes in southern Norway predicted for changes in non-marine sulfate concentration.

As with the previous analyses, it was assumed that the chemical conditions measured in a single sample are adequate to characterize the suitability of a lake to support fisheries. Water chemistry conditions are in fact extremely variable, and are particularly stressful at times of high flow during heavy autumn rain and snowmelt. Information is insufficient to evaluate the extent to which fisheries are determined by such episodic events, nor the degree to which SA and calcium in surface waters are governed by sulfate or acidity in deposition. Until such studies are reported a more realistic prediction, taking account of variable flow conditions, seems unlikely.

ALTERNATIVES

Since water quality, at least in terms of acidity, calcium and aluminum concentrations, appears crucial to fishery status, it follows that improvement is dependent on raising calcium and reducing aluminum, as well as reducing acidity. This has led to many attempts to restore lake fisheries by the application of limestone or similar materials to lakes, streams, or lake shores. This has been successful in reestablishing fisheries e.g. in Swedish lakes (Hasselrot and Hultberg, 1984), and in improving egg hatch and fry development (Rosseland and Skogheim, 1984) but has, in some cases, led to difficulties e.g. in aluminum precipitation, and in no benefit to the natural fishery (Gunn and Keller, 1984). Since both calcium and aluminum are derived principally from the catchment it seem preferable, at least in theory, to alter catchment yields than lake water directly, but field experiments seem few and effectiveness limited (Gunn and Keller, 1984).

Another method may be to manipulate drainage systems so as to improve the contact of drainage waters with pre-existing, or introduced, base materials within the soils of a catchment, or perhaps to divert acidic drainage from bogs or forests away from particularly susceptible, small, lakes. Although there is evidence in the United Kingdom that agriculture "improvement" and afforestation have both reduced total water runoff and increased runoff rates, no attempt appears to have been made to reverse hydrological changes.

Since lake acidification implies a progressive loss of neutralizing bases from catchment soils, addition of calcium or other minerals is an essential step to restoring affected lakes and streams. Techniques of soil/catchment treatment must be developed and tested so as to find effective and economic methods. These could be applied specifically to affected areas on a much shorter time scale than could ever be envisaged for national or international emission control and so would be both more certain and immediate. Such measures would also help to counteract natural acidification processes.

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FISH SPECIES DISTRIBUTION AS A FUNCTION OF LAKE ACIDITY IN THE NORTHEASTERN UNITED STATES

by

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SUMMARY

The northeastern United States now receives precipitation of annual volume weighted pH 4.3-4.4. A substantial portion of the surface waters in this region are low in alkalinity and are believed to be vulnerable to acidification from atmospheric deposition. The first reports of surface water acidification from precipitation and resulting adverse effects on fish populations in the United States were from the Adirondack Mountain region of New York. At least 17 lakes in this region have become acidified and have lost all fish populations. A recent survey of 28 lakes in Vermont found that the number of fish species and fish abundance were correlated with pH for lakes of pH <6.0. Two lakes that formerly supported fish were acidic (pH <5.0) and devoid of fish, although in one lake beaver activity could not be ruled out as a cause of the loss of fish.

We conducted a survey of water chemistry and fish species distribution and abundance in 23 Maine lakes. The lakes surveyed were similar in size and drainage type, had not been chemically reclaimed or stocked with hatchery fish, and were not affected by recent human acitivities in the watershed. The lakes had mean pH values between 4.7 and 7.0. There were no fish in two lakes with pH 4.7-4.9. All other lakes with pH $\geq$5.0 contained one or more species of fish. For lakes of pH 6.0 or greater there was no relationship between number of fish species or fish abundance and lake chemistry. However, for lakes of pH <6.0 both number of fish species and fish abundance were significantly correlated with lake pH.

INTRODUCTION

Acidic precipitation, defined as precipitation in all its forms that is contaminated with strong acids, now occurs in northern Europe, Great Britain, southern Scandinavia, and eastern North America. In south Norway and west-central Sweden, where the volume weighted annual average pH of precipitation is less than 4.6, large numbers of lakes and streams are now acidic (pH<5.0) and devoid of fish (Overrein et al. 1980). In the United States, precipitation of similar acidity occurs in all states east of Illinois and north of Florida. The first reports of acidic deposition-induced acidification of lakes and concomitant reductions in fish populations in North America were for the Adirondack Mountain region. Schofield (1976) surveyed 40 lakes that had been initially surveyed in the 1930s. In the 1930s three lakes had pH <5.0 and no fish and one lake with pH between 6.0 and 6.5 also had no fish. In 1975, 19 of these 40 lakes had pH <5.0 and had no fish. Two additional lakes with pH between 5.0 and 5.5 also lacked fish. Thus 17 lakes apparently lost fish populations during the interval between the 1930s and 1975.

In a recent survey, Colquhoun et al. (1984) found that the proportion of lakes with pH <5.0 was greater for lakes above 2,000 ft. elevation than for lakes below 2,000 ft. in the Adirondack region (Figure 27). For lakes above 2,000 ft., 44% (95 lakes) were pH <5, whereas only 13% (104 lakes) of lakes below 2,000 ft. elevation were this acidic. Of 289 lakes in the Adirondack region for which both fish and water chemistry data were available, 39% of those with pH <5.0 were devoid of fish whereas only 4% of those with pH >6.0 were fishless (Table 9).

Table 9. Summary of fish distribution by pH class for 289 waters with concurrent fish surveys and water chemistry (1975-1982).
Source: Colquhoun et al. 1984.

	pH classification		
	<5.0	5.0 to 6.0	>6.0
All waters sampled	33	93	163
Waters without fish	13	5	6
Waters with only non-trout species	5	11	35
Waters with trout/salmonid species	15	77	122

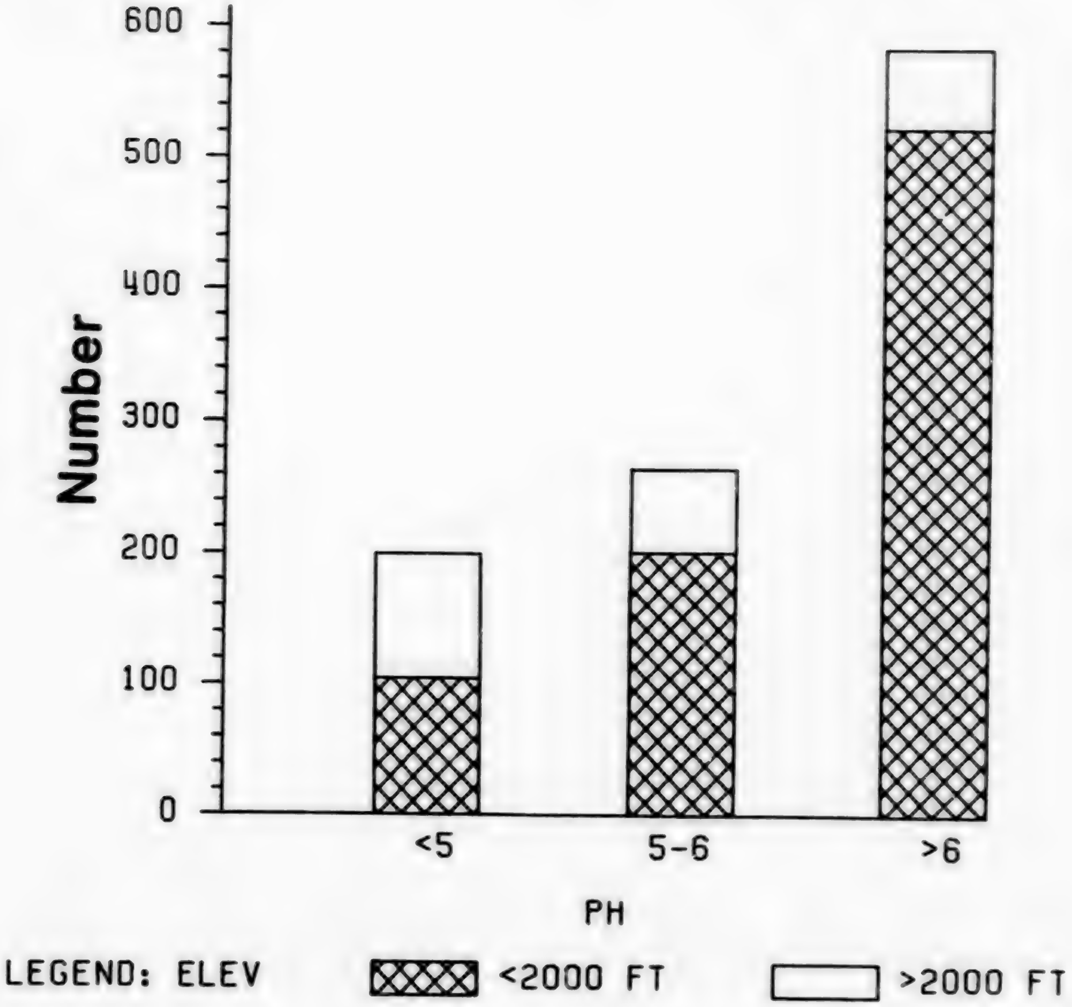

Figure 27. Distribution of lake pH for 1,047 Adirondack Mountain region lakes located at elevation below and above 2,000 ft. Source: Colquhoun et al.(1984)

VERMONT

Surveys of water chemistry and fish populations were conducted in 1982 and 1983 by the Vermont Agency of Environmental Conservation (Langdon 1983, 1984). The 28 lakes surveyed were selected from a set of 184 lakes that had been surveyed for water chemistry (Clarkson 1982) and were the lowest in alkalinity. The lakes surveyed were generally not affected by cultural disturbance. Most contained no permanent structures in the watershed, five contained seasonal dwellings, and only one contained year-round dwellings. Many of the lakes were stocked with salmonid fish, however, but only one lake contained only stocked salmonids. Each lake was visited once by a survey team. Fish were collected with experimental (variable mesh size) gill nets, baited minnow traps, and seines. Approximately equal fishing effort was expended at each lake.

Two of the lakes were fishless, and 27 contained one to 10 fish species. The two fishless lakes were known to have contained fish previously. One may have been affected by beaver activity, which blocked fish access to a spawning stream. No explanation other than acidification is apparent to explain the loss of fish from the other fishless lake. Inspection of the field data and review of laboratory toxicology data suggests that lakes with pH $\geq$6.0 should support relatively normal fish populations. Dividing the Vermont lakes into two groups based on pH (pH$\geq$5.0 and pH <6.0) and calculating the regression of $\log_{10}$ (number of species + 1) on pH gives the following results (Figure 28).

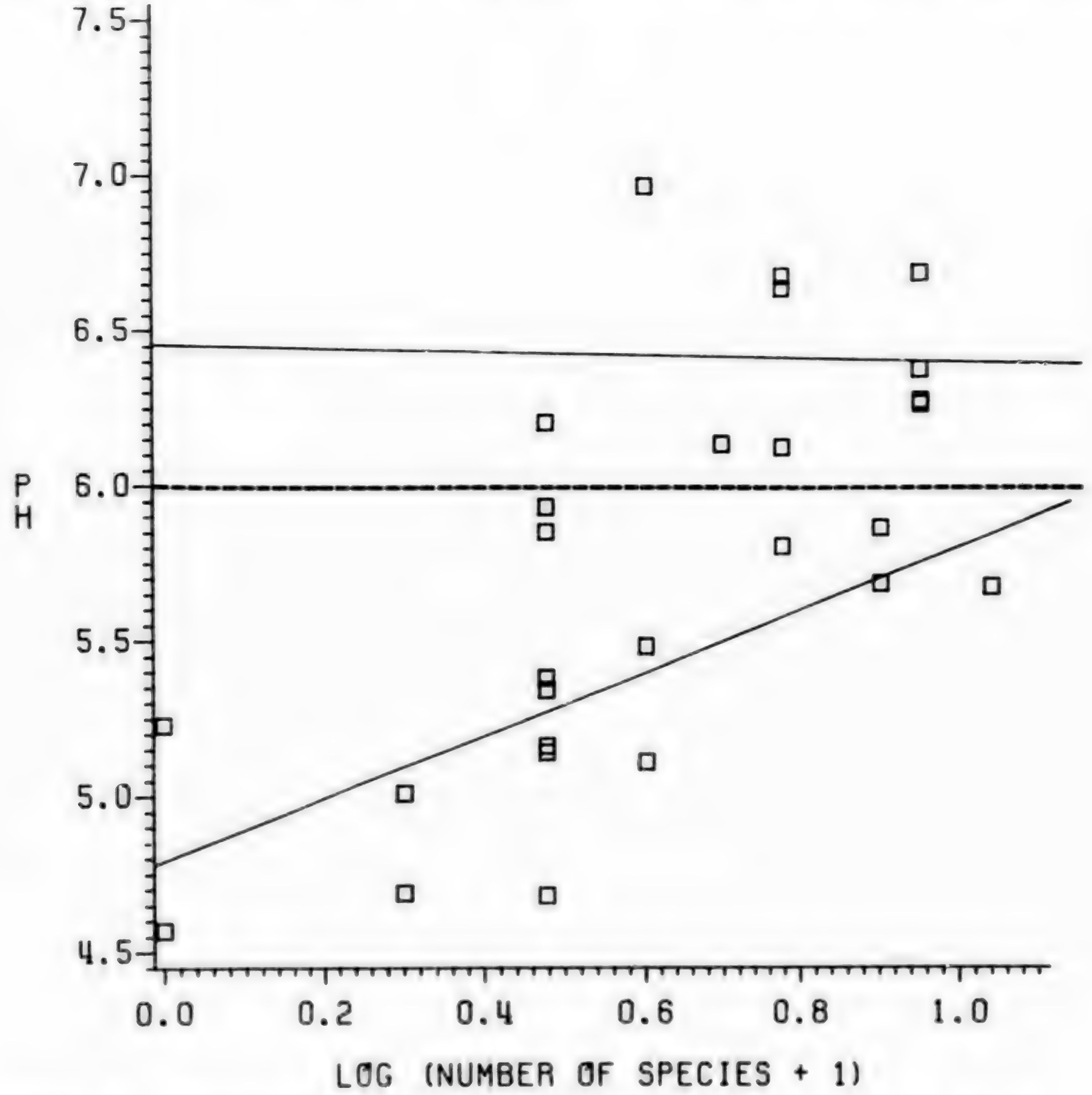

Figure 28. Regression of log (number of fish species + 1) on pH for 29 Vermont lakes. Source: Langdon (1983, 1984).

pH $\geq$6.0 pH = 6.47 - 0.08 log (Number of Species + 1)
r^2 = 0.002 p = 0.89 N = 11
pH <6.0 pH = 4.78 + 1.01 log (Number of Species + 1)
r^2 = 0.38 p = 0.006 N = 18

As expected, there is no significant regression for lakes with pH≥6.0, but there is for the more acidic lakes.

Fish abundance, expressed as catch per sample per day (a standard unit of effort), was also related to lake acidity in Vermont. The regression of log (catch per unit effort + 1) on pH was significant (Figure 29), but the association was weak. Lakes were again divided into two groups based on pH and the regressions repeated:

pH ≥6.0 $pH = 6.34 + 0.03 \log$ (Catch per Unit Effort + 1)
$r^2 = 0.003$ $p = 0.88$ $N = 11$
pH <6.0 $pH = 4.84 + 0.30 \log$ (Catch per Unit Effort + 1)
$r^2 = 0.30$ $p = 0.018$ $N = 18$

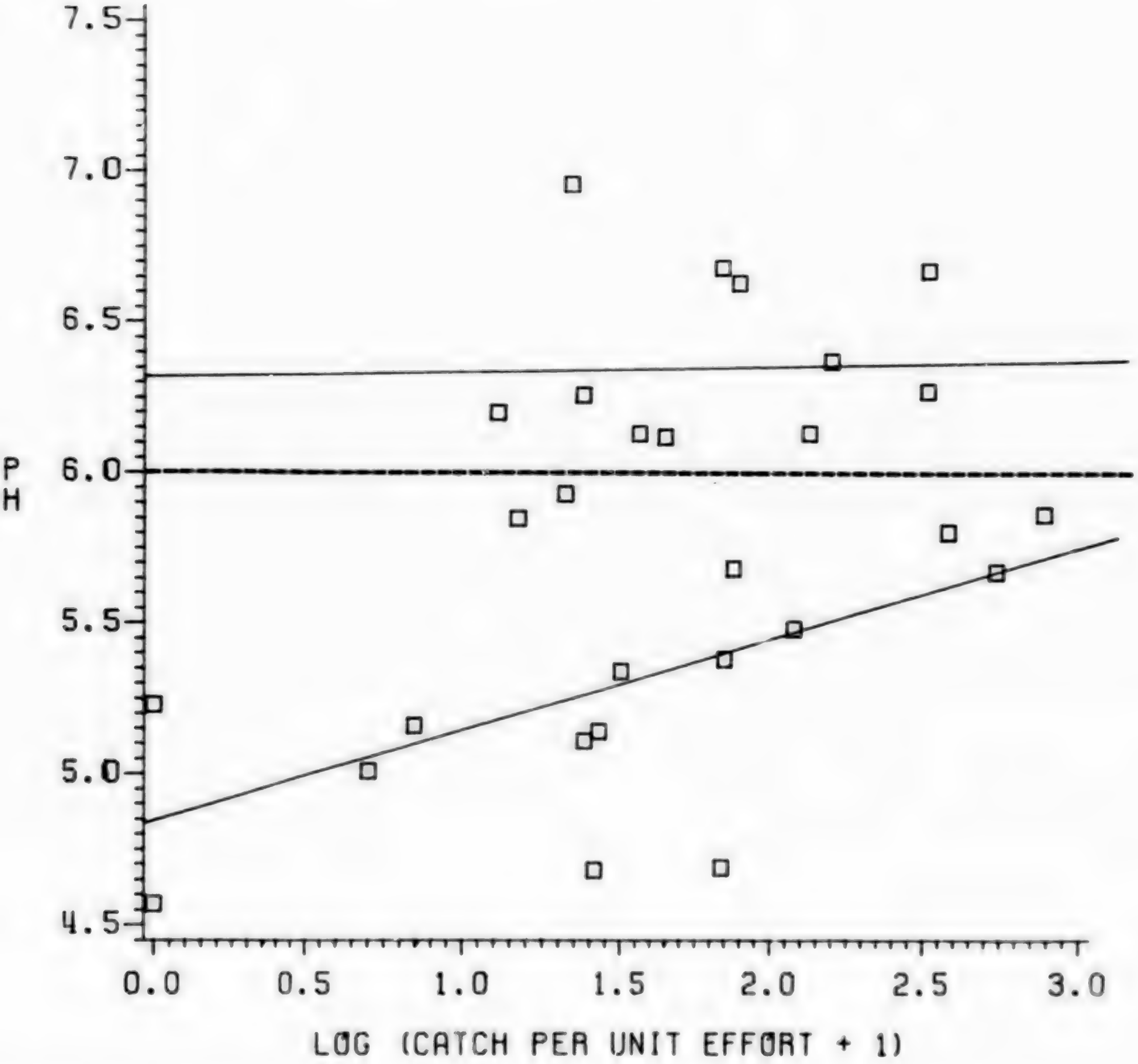

Figure 29. Regression of log (catch per unit effort + 1) on pH for 29 Vermont lakes. Source: Langdon (1983, 1984).

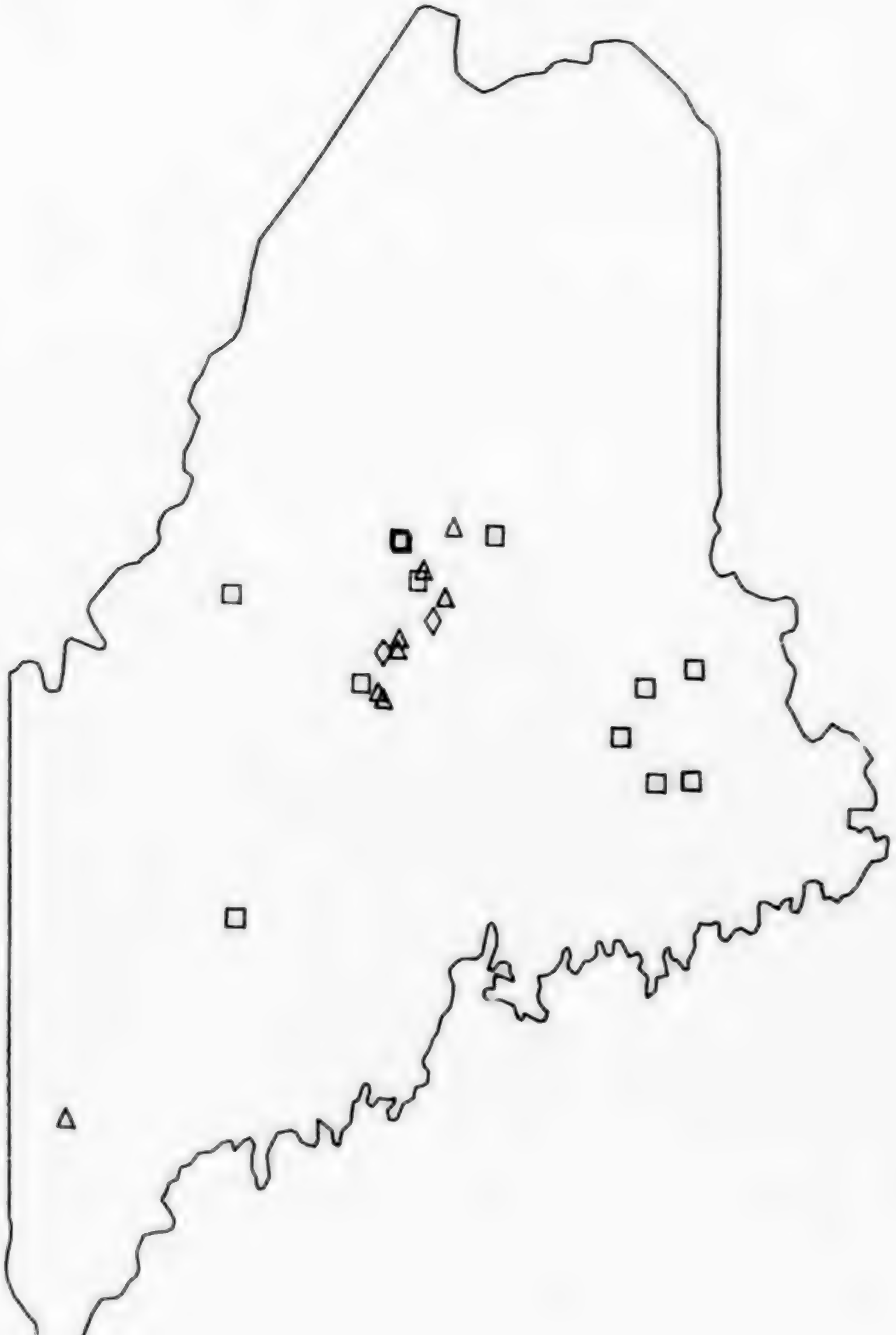

Figure 30. Geographical distribution and pH category for 23 lakes surveyed in Maine.

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As expected, the regression was not significant for lakes of pH ≥6.0 and was significant for the more acidic lakes, although the coefficient of determination is still low.

MAINE

We selected 23 Maine lakes for a survey of the effects of water chemistry on fish species distribution and abundance (Figure 30). The lakes selected were small (<40 ha), low-color (<30 Hazen units), headwater drainage lakes that had not been reclaimed or stocked with hatchery fish. They were sufficiently remote from vehicle access as to make excessive fishing pressure or baitfish introductions unlikely. The watersheds were uninhabited and completely forested, with no evidence of recent watershed disturbance. Each lake was visited three times (spring, summer, fall) by a survey team. At each visit water samples were collected from just under the surface and just over the bottom at the deepest point in the lake. The samples were analyzed for pH, inflection-point alkalinity, specific conductance, and apparent color immediately, and subsamples were preserved for future analysis of all major cations (Ca, Mg, Na, K, total Al) and anions (SO_4, NO_3, Cl, F). Details of water sample collection and analysis are given in Haines and Akielaszek (1983).

Each lake was surveyed once, during summer, to determine fish species presence and abundance. A standard fish sampling protocol was used in each lake. Two experimental gill nets (mesh size 1/2", 3/4", 1", 1 1/4", and 1 1/2" square measure) and six wire mesh (1/4" square measure) baited minnow traps were set from mid-afternoon to mid-morning the following day. All fish captured were identified to species and enumerated.

All lakes surveyed were clear, soft-water lakes, with specific conductance values ranging from 13 to 28 μS/cm (Table 10).

Table 10. Physical and chemical data for 22 lakes surveyed in Maine.

Lake	Surface Area (ha)	Maximum Depth (m)	pH (units)	Alkalinity (μeq/l)	Specific Conductance (μS/cm)	Color (Hazen units)
Browns	39	2	5.85	22	21	45
Porter	23	4	6.42	46	20	20
Green	26	4	7.02	112	25	10
Davis	7	11	6.14	65	26	63
Upper Pug	20	5	6.73	94	25	17
Johnston	24	18	6.10	28	15	6
Twin	24	26	6.33	57	22	8
Garcock	1	6	5.55	18	20	41
Crater	6	8	4.81	-10	16	0
Cloud	8	11	4.77	-14	21	10
Lost	6	3	5.41	6	18	34

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Table 10 concluded.

Lake	Surface Area (ha)	Maximum Depth (m)	pH (units)	Alkalinity (µeq/l)	Specific Conductance (µS/cm)	Color (Hazen units)
Little Hurd	24	27	6.02	31	20	0
Big Fisher	23	3	6.53	82	22	23
Little Fisher	14	2	6.26	46	25	41
Unnamed	7	2	5.87	24	17	64
Eighteen	6	9	6.05	23	14	13
Fogg	9	6	6.06	19	13	6
Horseshoe	26	4	5.63	7	17	26
Bear	5	4	6.44	82	21	57
Knox	21	6	6.23	43	22	36
Trout	2	3	6.76	90	28	13
E. Chairback	18	18	5.00	-6	18	0

However, they differed considerably in acidity. The mean pH values ranged from 4.7 to 7.0. In all, species of fish representing 11 families were collected from the 22 lakes surveyed (Table 11), but only three (brook trout, golden shiner, white sucker) were widely distributed. The average number of species per lake was four (range 0 to 9).

Table 11. List of fish species found in the 22 lakes surveyed in Maine.

Family	Common Name	Scientific Name	Freq. of Occurrence
Salmonidae	Brook trout	*Salvelinus fontinalis*	11
	Sunapee trout	*Salvelinus alpinus*	1
Osmeridae	Rainbow smelt	*Osmerus mordax*	1
Esocidae	Chain pickerel	*Esox niger*	5
Cyprinidae	Golden shiner	*Notemigonus crysoleucas*	12
	Blacknose dace	*Rhinichthys atratulus*	2
	Common shiner	*Notropis cornutus*	7
	Rosyface shiner	*Notropis rubellus*	1
	No. Redbelly dace	*Chrosomus eos*	2
	Finescale dace	*Chrosomus neogaeus*	2
	Fathead minnow	*Pimephales promelas*	3
	Creek chub	*Semotilus atromaculatus*	6
	Fallfish	*Semotilus corporalis*	3
	Pearl dace	*Semotilus margarita*	2
Catostomidae	White sucker	*Catostomi commersoni*	10
Ictaluridae	Brown bullhead	*Ictalurus nebulosus*	4
Anguillidae	American eel	*Anguilla rostrata*	1

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Table 11 concluded.

Family	Common Name	Scientific Name	Freq. of Occurrence
Cyprinodontidae	Banded killifish	*Fundulus diaphanus*	2
Percichthydae	White perch	*Morone americana*	1
Centrarchidae	Redbreast sunfish	*Lepomis auritus*	3
	Pumpkinseed	*Lepomis gibbosus*	2
Percidae	Yellow perch	*Perca flavescens*	2

The distribution of fish species that occurred in three or more collections is compared to lake pH in Figure 31.

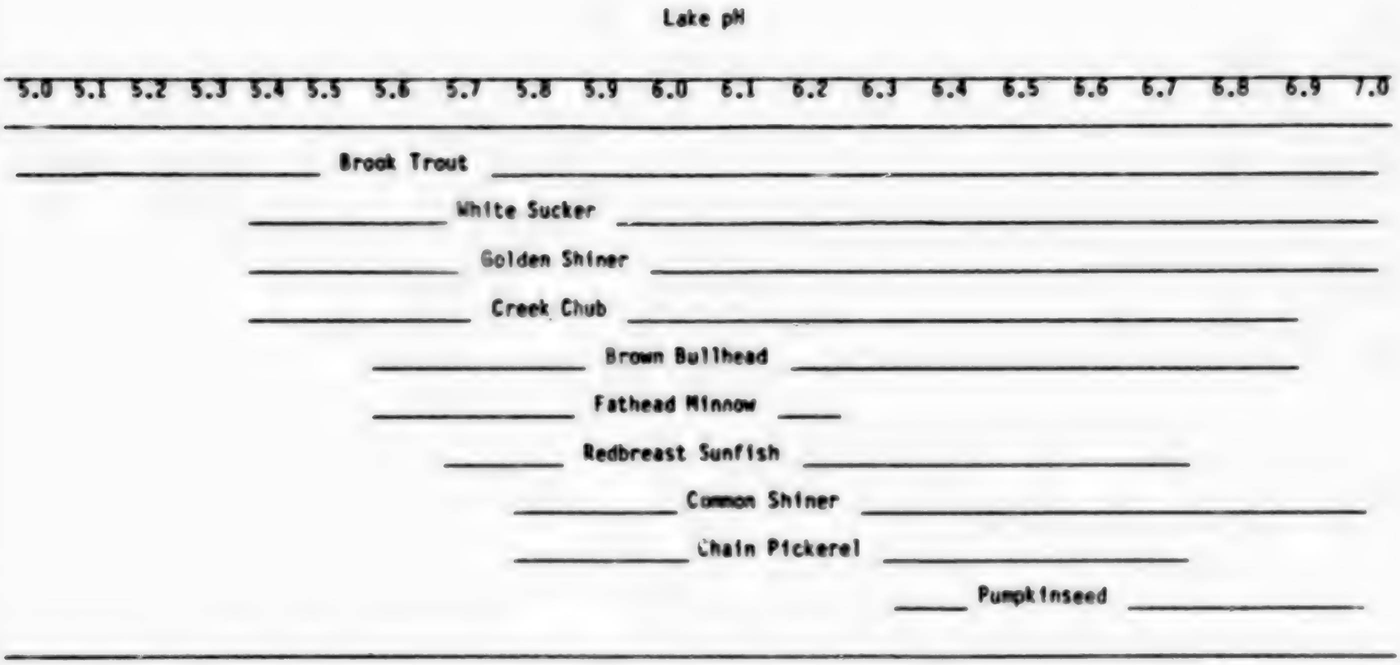

Figure 31. Distribution of fish species by lake pH. Only species that were collected from three or more lakes are shown. Species presence is indicated by a solid line.

Brook trout occurred over the widest range of lake pH (5.0 to 7.0). White sucker, golden shiner, and creek chub were nearly as widely distributed, occurring down to pH 5.4. Pumpkinseed was the most restricted species, not being found below pH 6.3.

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For comparison of number of species and abundance to lake chemistry, the lakes were divided into two groups: pH $\geq$6.0 and pH <6.0. The regression of $\log_{10}$ (number of species + 1) on pH gave the following results (Fig. 32):

pH $\geq$6.0 pH = 5.95 + 0.75 log (Number of Species + 1)
$r^2 = 0.13$ $p = 0.19$ $N = 15$
pH <6.0 pH = 4.86 + 1.16 log (Number of Species + 1)
$r^2 = 0.77$ $p = 0.004$ $N = 8$

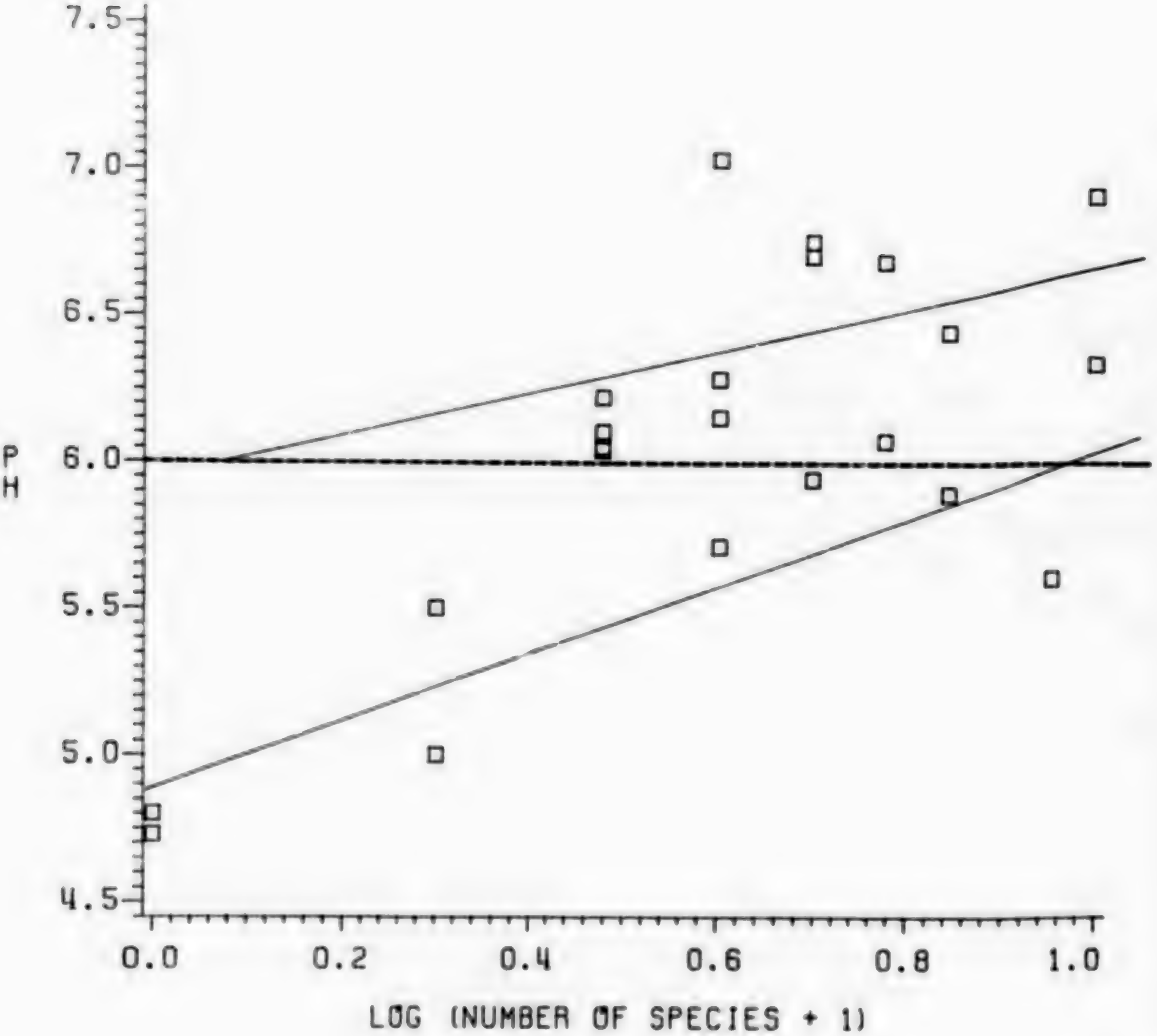

Figure 32. Regression of log (number of fish species + 1) on pH for 22 Maine lakes.

As expected, the regression is not significant for lakes of pH ≥6.0, but is for more acidic lakes. The form of the regression is very similar to that for acidic Vermont lakes. A similar analysis was conducted for fish abundance, expressed as catch per unit effort (Figure 33):

pH ≥6.0 pH = 6.01 + 0.23 log Catch per Unit Effort + 1)
$r^2 = 0.08$ p = 0.32 N = 15
pH <6.0 pH = 4.79 + 0.42 log (Catch per Unit Effort + 1)
$r^2 = 0.83$ p = 0.002 N = 8

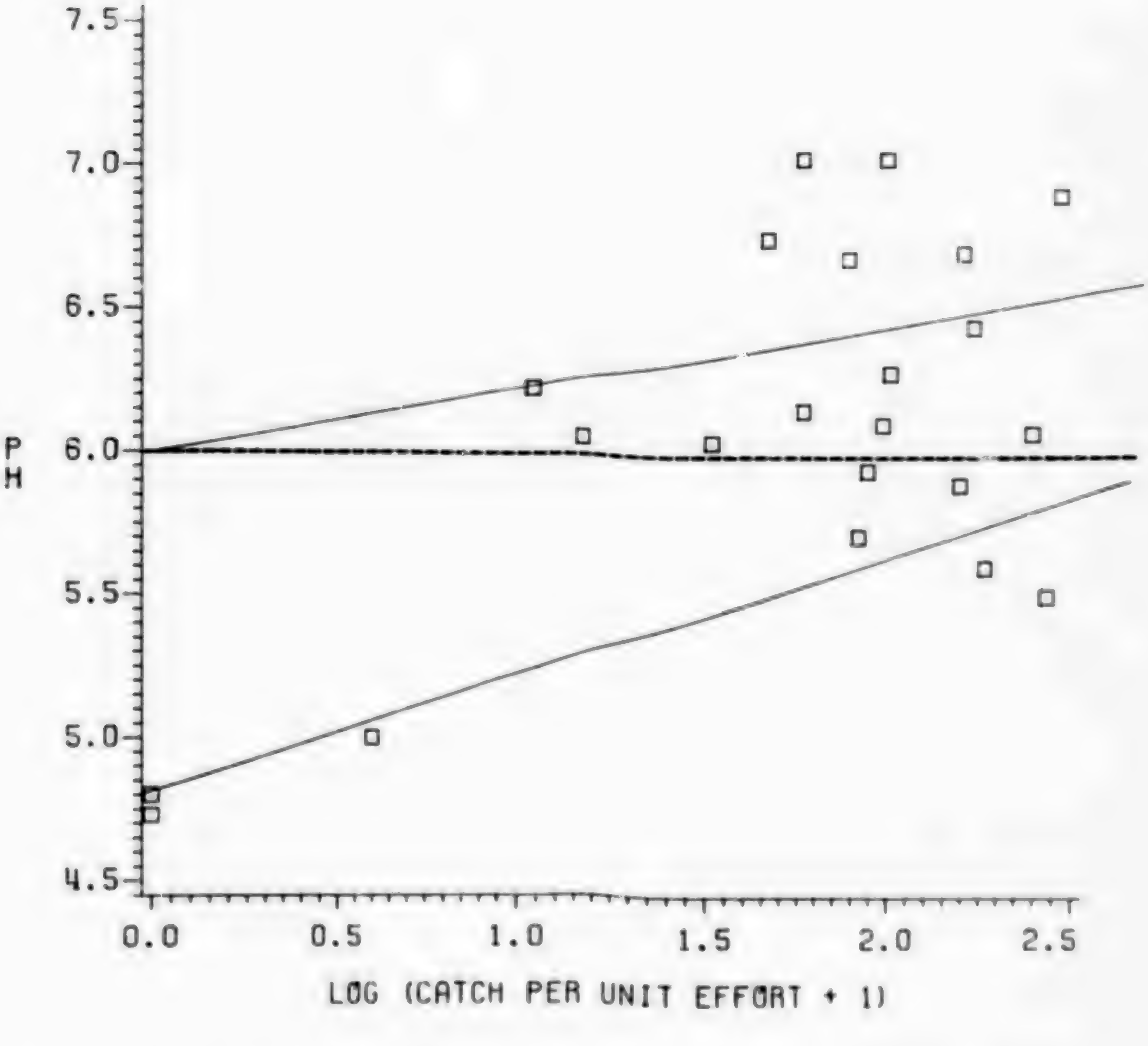

Figure 33. Regression of log (catch per unit effort + 1) on pH for 22 Maine lakes.

Again, the regression is not significant for lakes of pH ≥6.0 but is for more acidic lakes, and the form of the regression is similar to that for acidic Vermont lakes.

DISCUSSION

Acidic precipitation has apparently not caused widespread acidification of surface waters with concomitant loss of fish populations in the northeastern United States as it has in southern Scandinavia. The areas in the northeastern United States that contain acidic lakes is relatively small as is the number of acidic lakes. The most affected area is the Adirondack Mountain region of New York. At least 17 lakes in this region have been acidified and have lost all fish populations (Schofield 1976; Colquhoun et al. 1984). The number of lakes that have been affected and lost at least some acid-sensitive fish species is undoubtedly much larger. A survey of 1,200 lakes now being conducted in New York will provide much-needed information concerning the actual extent of acid-related fishery damage in this area.

A survey of 184 lakes in Vermont identified 43 (34%) with pH <6.0 and 7 (4%) with pH <5.0 (Clarkson 1982). A fishery survey of 28 of the lowest pH lakes that were suitable for such surveys (Langdon 1983, 1984) identified two acidic, fishless lakes. Both were known to formerly support fish. In one case, beaver activity could not be ruled out as a cause of the demise of the fish population. In the other case, however, acidification was the only possible explanation for the disappearance of the fish. Regression of the number of fish species present and relative abundance of fish in lakes with pH <6.0 indicated that the number of species present and the abundance of fish declined significantly with decreased pH. It is possible that acidic deposition has decreased lake pH and caused the loss of some fish populations in these lakes, even though historical fisheries records are inadequate to document such an occurrence.

The proportion of acidic, fishless lakes, and the relationship between lake pH and fish species distribution and relative abundance of the lakes we surveyed in Maine is remarkably similar to the results from Vermont. In as much as the lakes we surveyed had generally not been surveyed previously, there are no records to indicate whether the lakes that are presently fishless ever supported fish. However, these lakes are physically similar to many nearby lakes and there is no *a priori* reason to suspect that these lakes have always been devoid of fish. The similarity in the relationship between lake chemistry and fish species presence and abundance for Vermont and Maine lakes is not surprising considering that these two areas are relatively similar in topography, climate, and zoogeography, and receive precipitation that is similar in chemistry (Interagency Task Force on Acid Deposition 1983).

Although the number of acidic, fishless lakes in the northeastern United States is not large at present, there is reason for concern for the future of the fisheries resource in this area. A survey of headwater lakes and streams in this region found that more than 40% had alkalinity values less than 100μ eq/l (Haines and Akielaszek 1983), and therefore are highly susceptible to acidification. If acidic deposition continues or intensifies, the proportion of acidic, fishless lakes could increase substantially in the future.

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50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO.
Biol. Rep. 80(40.21)

2.

3. Recipient's Accession No.

4. Title and Subtitle
Acid Rain and Fisheries: A Debate of Issues
Symposium Proceedings, American Fisheries Society
114th Annual Meeting

5. Report Date
October 1985

6.

7. Author(s)
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8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Eastern Energy and Land Use Team
U.S. Fish and Wildlife Service
Box 705
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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
U.S. Department of Interior, Fish and Wildlife Service,
Division of Biological Services, Eastern Energy and Land
Use Team, Box 705, Kearneysville, WV 25430

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The complexity of the acid deposition problem has led to debate in the United States and the international community. A symposium was held at the 114th Annual Meeting of the American Fisheries Society with the purpose of focusing discussion on some of the more controversial aspects of acidic deposition and its effects on fish. To that end, scientists with disparate views on key issues were asked to present their case before the Society. This volume includes six of the papers presented at the symposium and two extended abstracts. Topics covered the complexity of decision making at the National level, the role of science in the legislative process, how natural processes and land use practices must be considered as factors responsible for decreased pH, how estimating fish losses cannot be based on pH alone, experimental evidence demonstrating that low pH and aluminum decrease hatching of brook trout, and a summary of field and laboratory evidence for Ontario and a description of ongoing research. It is hoped these papers will contribute to the timely debates of acid deposition effects and emphasize some of the more important scientific questions awaiting resolution.

17. Document Analysis a. Descriptors

Acidification, pH, aluminum, calcium, sulfur dioxide, nitrogen oxide, regulatory emission controls, fisheries , acid deposition

b. Identifiers/Open-Ended Terms

Acid rain, circumneutral waters, acidic waters, fish, transported air pollutants

c. COSATI Field/Group

18. Availability Statement
Unlimited

19. Security Class (This Report)
unclassified

20. Security Class (This Page)
unclassified

21. No. of Pages
ix + 95

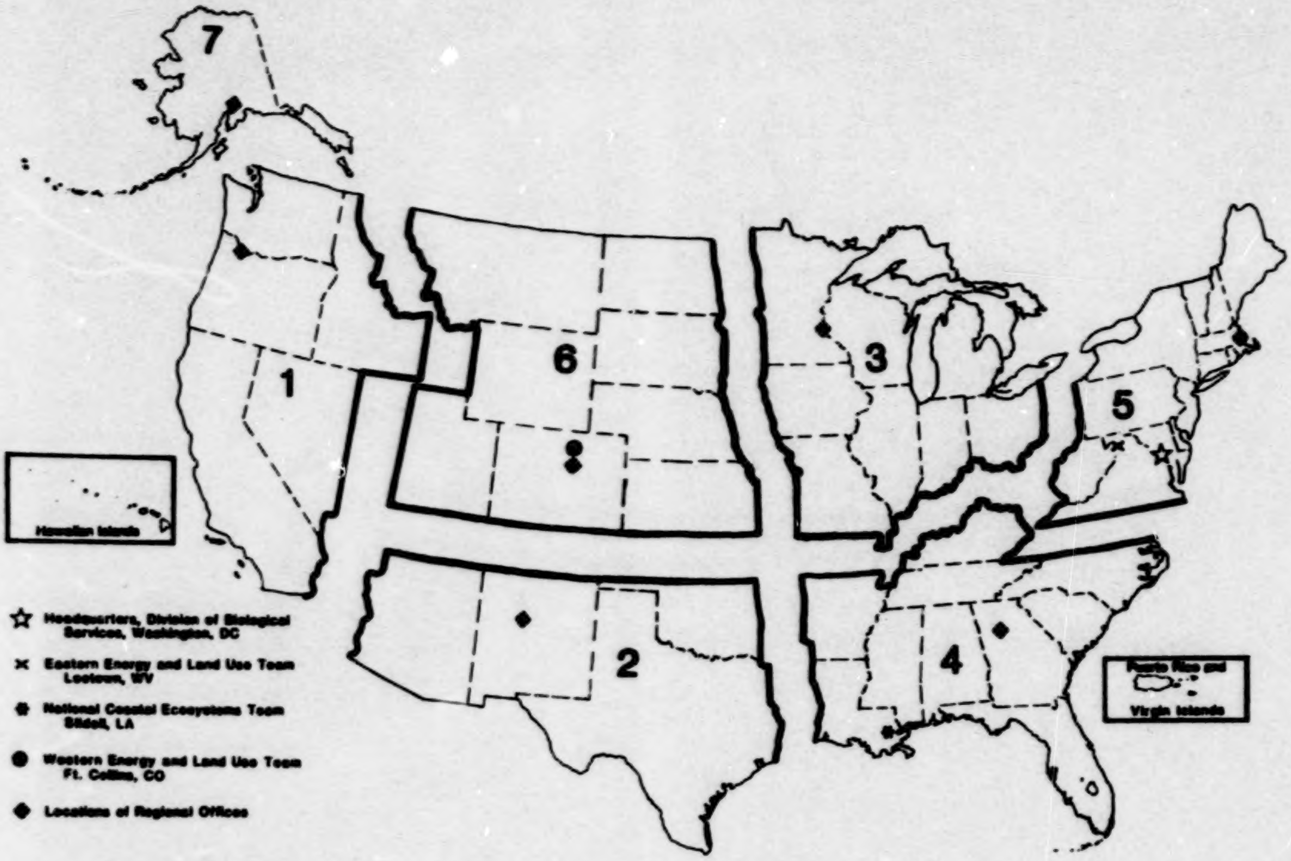
22. Price

(See ANSI–Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4–77)
(Formerly NTIS–35)
Department of Commerce

☆U.S. GOVERNMENT PRINTING OFFICE:1986—676-818/45030

96.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